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RESEARCH AND DEVELOPMENT OF A LOW-COST, PORTABLE VISUAL FIELD TESTING PLATFORM USING A SMARTPHONE AND VIRTUAL REALITY HEADSET FOR THE EARLY DETECTION OF GLAUCOMA

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Research and development of a low-cost, portable visual field testing platform using a smartphone and virtual reality headset for the early detection of glaucoma

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Dissertation presented in partial fulfillment of the requirements for the degree of Doctor of Engineering Technology (PhD)

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Abstract

Glaucoma is the leading cause of irreversible blindness worldwide, affecting about 64 million people. A large proportion of glaucoma cases worldwide are undiagnosed or sub-optimally managed. More than half of people living with the disease, in low-income countries, are unaware of the condition until it progresses to an advanced stage, resulting in visual impairment. Since adequate treatment significantly slows or halts progression of the disease, early detection of cases is considered important. Visual field test is one of the major tests for screening and diagnosis of glaucoma. The test assesses central and peripheral vision of each eye separately in order to detect vision loss, which, in case of glaucoma, gradually progresses from the periphery to the center. The test is mostly performed with standard automated perimetry equipment which is expensive and not easily portable. For people living in rural areas of low-income countries with limited access to ophthalmic care, glaucoma screening and diagnosis testing through visual field test is near inexistent. If an affordable alternative to the standard automated perimetry(SAP) equipment would become available, it is likely that more glaucoma cases could be detected, especially in rural areas where the burden of the disease is most significant.

This doctoral dissertation describes the design, development and assessment of a smartphone based low-cost and portable glaucoma visual field screening platform. This doctoral dissertation aims to explore the feasibility of a low-cost and portable visual field screening platform for the early detection of glaucoma, using a smartphone and a virtual reality(VR) headset. To address this aim, the following research questions will be answered.

RQ1: What are the needs and preferences of ophthalmic professionals and patients in rural areas of developing countries towards a visual field screening platform using smartphone and VR headset?
RQ2: How do we design and develop a mobile app for visual field screening tailored to the needs of ophthalmic professionals and patients from rural areas?
RQ3: What are ophthalmic professionals' use and acceptance of a glaucoma screening platform using smartphone and VR headset?

RQ4: What is the accuracy of a glaucoma screening platform using smartphone and VR headset compared to a gold standard perimetry equipment?
RQ5: What is the sensitivity and specificity of a glaucoma screening platform using smartphone and VR headset?

An adopted version of the user-centered design (UCD) process was followed to address most of the research questions. First, a user and task analysis is conducted in Southwest Ethiopia to identify requirements for a visual field screening application. Multiple contextual requirements were identified during this step using field observations, semi-structured interviews with ophthalmic professionals and patients. Next, design parameters and devices (smartphone and VR headset) were selected based on the requirements identified. Next, a prototype screening Android app, glaucoma easy screener(GES), is developed. Following this, the screening app was assessed for usability and acceptability among ophthalmic professionals in Southwest Ethiopia. OPs perceived GES as easy-to-use, enabling the screening of glaucoma screening tests, especially during outreach to rural areas. Even older patients from rural areas, with limited familiarity with technology, were able to perform the test with GES, and valued a 'technical' assessment. Next, clinical accuracy of GES was evaluated by comparing its results against gold standard SAP equipment. There was good level of agreement (above 85%) based on results of 36 eyes. Finally, an assessment of sensitivity and specificity was conducted by testing 40 glaucomatous eyes and 20 normal eyes with the screening platform. Receiver Operator Characteristic (ROC) was used to determine an optimal cut-off points that yields the best combination of sensitivity and specificity. A cut-off value of 3 missed point yielded an acceptable trade-off between sensitivity (90%) and specificity (85%).

These findings suggest that low-cost and portable glaucoma visual field screening using smartphone and VR headsets is feasible.

Beknopte samenvatting

Glaucoma is wereldwijd de belangrijkste oorzaak van onomkeerbare blindheid en treft ongeveer 64 miljoen mensen. Een groot deel van de glaucomagevallen wereldwijd wordt niet gediagnosticeerd of suboptimaal behandeld. Meer dan de helft van de mensen in lage-inkomenslanden die met de ziekte leven, zijn zich niet bewust van de aandoening totdat deze in een vergevorderd stadium is gekomen, met visuele beperkingen tot gevolg. Aangezien een adequate behandeling de progressie van de ziekte aanzienlijk kan vertragen of tot stilstand brengen, wordt een vroegtijdige opsporing van de gevallen van groot belang geacht. De gezichtsveldtest is een van de belangrijkste tests voor de screening en diagnose van glaucoma. De test beoordeelt het centrale en perifere gezichtsvermogen van elk oog afzonderlijk om gezichtsverlies op te sporen dat, in geval van glaucoma, geleidelijk van de periferie naar het centrum overgaat. De test wordt meestal uitgevoerd met standaard geautomatiseerde perimetrieapparatuur, die kostbaar en niet gemakkelijk draagbaar is. Voor mensen die in landelijke gebieden van lage-inkomenslanden wonen met beperkte toegang tot oogheelkundige zorg, is screening en diagnose van glaucoma door middel van een gezichtsveldtest vrijwel onbestaande. Indien een betaalbaar alternatief voor de standaard geautomatiseerde perimetrie (SAP) apparatuur beschikbaar zou komen, is het waarschijnlijk dat meer glaucoma gevallen kunnen worden opgespoord, vooral in landelijke gebieden waar de last van de ziekte het grootst is.

Dit proefschrift beschrijft het ontwerp, de ontwikkeling en de evaluatie van een smartphone-gebaseerd goedkoop en draagbaar platform voor gezichtsveldtesten. Dit proefschrift heeft als doel de haalbaarheid te onderzoeken zo een platform voor de vroege detectie van glaucoma, met behulp van een smartphone en een virtual reality (VR) headset. Om dit doel te bereiken, zullen de volgende onderzoeksvragen beantwoord worden.

RQ1: Wat zijn de behoeften en voorkeuren van oogheelkundige professionals en patiënten in rurale gebieden van ontwikkelingslanden ten opzichte van een gezichtsveltestplatform met behulp van een smartphone en VR headset?

RQ2: Hoe ontwerpen en ontwikkelen we een mobiele app voor gezichtsveldscreening afgestemd op de behoeften van oogheelkundige professionals en patiënten uit rurale gebieden?

RQ3: Wat is het gebruik en de acceptatie door oogheelkundige professionals van een glaucoma screeningsplatform met behulp van smartphone en VR headset?

RQ4: Wat is de nauwkeurigheid van een glaucoom screeningsplatform met behulp van smartphone en VR headset in vergelijking met een gouden standaard perimetrie apparatuur?

RQ5: Wat is de sensitiviteit en specificiteit van een glaucoom screeningsplatform met behulp van smartphone en VR headset?

Een aangepaste versie van het user-centered design (UCD) proces werd gevolgd om de meeste van de onderzoeksvragen te beantwoorden. Eerst is een gebruikers- en taakanalyse uitgevoerd in Zuidwest Ethiopië om de vereisten voor een applicatie voor gezichtsveldscreening te identificeren. Meerdere contextuele vereisten werden geïdentificeerd tijdens deze stap met behulp van veldobservaties, en semi-gestructureerde interviews met oogheelkundige professionals en patiënten. Vervolgens werden ontwerpparameters en apparaten (smartphone en VR-headset) geselecteerd op basis van de geïdentificeerde vereisten. Vervolgens is een prototype screening Android app, Glaucoma Easy Screener (GES), ontwikkeld. Vervolgens werd de screeningsapp beoordeeld op bruikbaarheid en aanvaardbaarheid door professionals in de oogheelkunde in Zuidwest-Ethiopië. Zij ervoeren GES als gemakkelijk te gebruiken, waardoor het screenen van glaucoom screening tests mogelijk werd, vooral tijdens veldwerk in landelijke gebieden. Zelfs oudere patiënten uit plattelandsgebieden, met een beperkte vertrouwdheid met technologie, waren in staat om de test uit te voeren met GES, en waardeerden een 'technische' beoordeling. Vervolgens werd de klinische nauwkeurigheid van GES geëvalueerd door de resultaten te vergelijken met de gouden standaard SAP-apparatuur. Er was een goede mate van overeenstemming (meer dan 85%) op basis van de resultaten van 36 ogen. Ten slotte werd de sensitiviteit en specificiteit beoordeeld door glaucomateuze ogen en 20 normale ogen te testen met het screeningplatform. Receiver Operator Characteristic (ROC) werd gebruikt om een optimaal grenswaardepunt te bepalen dat de beste combinatie van gevoeligheid en specificiteit oplevert. Een drempelwaarde van 3 gemiste punten leverde een aanvaardbare afweging op tussen sensitiviteit (90%) en specificiteit (85%).

Deze bevindingen suggereren dat low-cost en draagbare glaucoom visuele veld screening met behulp van smartphone en VR headsets haalbaar is.

List of Abbreviations

AUC area under the curve, 90
BI behavioral intention, 70
dB decibels, 44
EE effort expectancy, 57
FC facilitating conditions, 57
FDT frequency doubling technology, 9
GES glaucoma easy screener, 13
GST glaucoma screening test, 42
HFA humphrey field analyzer, 5
IOP intraocular pressure, 2
JUMC Jimma university medical center, 21
LIC low-income country, 18
mHealth mobile health, 54
NGO non-governmental organization, 8
OP ophthalmic professional, 13
PE performance expectancy, 57
PEEK portable eye examination kit, 56
PP portable perimeter, 80
ROC receiver-operating-characteristic, 90
SAP standard automated perimetry, 5
SaPH Saja primary hospital, 21
SCPH Seka Chokorsa primary hospital, 21
SI social influence, 57
TT trachoma trichiasis, 22
UCD user-centered design, 11
UTAUT unified theory of acceptance and use of technology, 56
VFT visual field testing, 20
VR virtual reality, 10

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Chapter 1

General Introduction

1.1 Glaucoma

The human eye consists of optic nerves which are located at the back of the eye attached to the retina. These nerves send light signals to the brain [1], [2]. They are composed of retinal ganglion cell axons and glial cells [3], [4]. Glaucoma is one of several diseases that can affect the optic nerve. It is an optic neuropathy characterized by progressive degeneration of the optic nerve and loss of retinal ganglion cells [5]–[7]. If untreated, the disease results in vision loss in affected areas gradually spreading to other areas, which may eventually result in complete loss of the vision in that eye [8]. The typical visual field defect from glaucoma often occurs first in the peripheral field of vison and can increase to form a larger defect in the central field of vision as shown on Figure 1.1 [7], [9].



Figure 1.1 Sample view with an advanced vision loss from glaucoma (source http://www.nei.nih.gov)

Glaucoma is the leading cause of irreversible blindness worldwide, affecting about 64 million people [10], [11]. A large proportion of these glaucoma cases are undiagnosed or sub-optimally managed [12]. Due to the slow and typically painless progression of visual field damage, patients with glaucoma commonly do not experience any problems with their vision until they have a significant level of visual loss [13], [14].

More than half of the people living with the disease, in low-income countries, are unaware of the condition until it progresses to an advanced stage, resulting in visual impairment [15], [16]. The major challenge in diagnosing the disease comes from its asymptomatic nature. Detecting glaucoma becomes even a more complicated issue in low-income countries due to the limited access to ophthalmic eye care facilities by large part of the population [13]. Unlike most

of the population in developed countries, people in low-income countries cannot afford or do not have access to regular eye examinations, which are critical for glaucoma detection.

Vision loss due to glaucoma can be slowed or even halted by appropriate treatment in most cases [17]. Since adequate treatment significantly slows progression of the disease [18], [19], the early detection of cases is considered important [20].

Tests for screening and detection of glaucoma involve three components: (1) an assessment of structural changes at the optic nerve head by fundoscopy or imaging to examine the retina and optic nerve, (2) functional visual loss by visual field testing, and (3) the level of the intraocular pressure (IOP) [21], [22]. IOP measurement is a key test as a majority of glaucoma cases is associated with elevated IOP [23]. The visual field test, which is the focus of this PhD thesis, is considered to be an essential component of these tests [24].

1.2 The Normal Visual Field

Visual field refers to the portion of space in which objects are visible at the same moment during steady fixation of gaze. It is measured in degrees of the viewing angle [25]. On average, the monocular (single eye) visual field covers 60 degrees superiorly/upwards, 75 degrees inferiorly/downwards, 100 degrees to the temporal side and 60 degrees nasal (towards the nose) (see Figure 1.2). Thus, the visual field approximately covers 160 degrees in width and 135 degrees in height [26], [27].

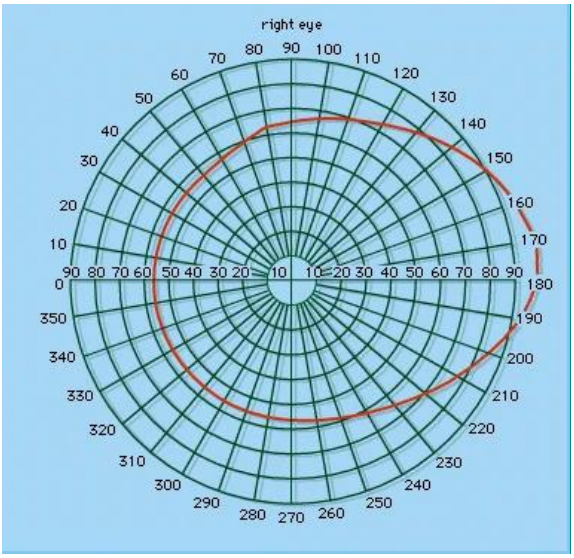


Figure 1.2 Normal visual field of right eye (source Encyclopædia Britannica, Inc.).

Meanwhile, the binocular visual field of the two eyes overlaps in the central area, with an approximate width of 200 degrees and a height of 120 degrees [25], [28] (see Figure 1.3).

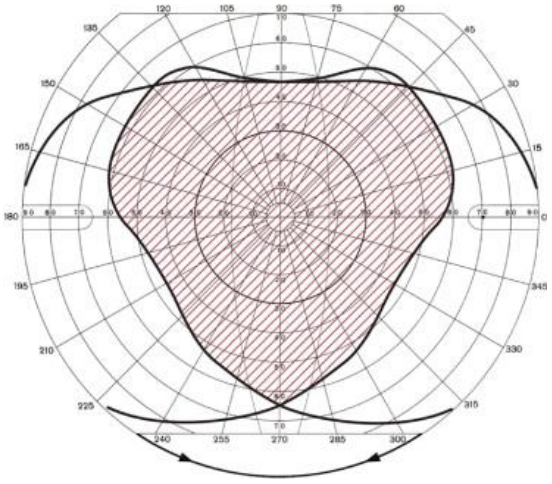


Figure 1.3 Binocular visual field of two eyes with an overlap in the central area (source Kakizaki et.al [29])

Visual sensitivity refers to the dimmest light stimulus that can be detected and is not uniform throughout the visual field. The visual field is usually represented as a hill, or island of vision [30] (see Figure 1.4). The small central

region, called the fovea, has the highest visual sensitivity. It decreases proportionally depending on distance from the fovea with the peripheral field of view only capable of discriminating movement. Therefore, when exploring an environment, the eyes constantly move towards the object of interest, in order to get the maximal information. Age affects the normal hill of vision [31], [32]. Sensitivity to light decreases with increasing age beginning from the age of 20 onwards [33], [34].

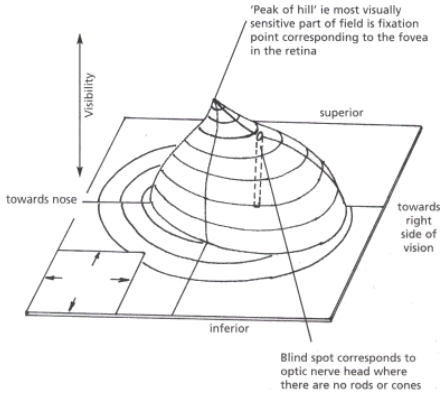


Figure 1.4 Hill (Island) of vision representing visual sensitivity. The tip of the hill represents high sensitivity at the fovea and bottom of the hill represents peripheral vision with lower sensitivity. (Source entokey.com)

Every human eye has an area of complete blindness in the visual field, called the blind spot. It corresponds to the position of the optic disk (optic nerve head) with in the retina. Since there are no photoreceptors in this area, there is no image detection [25], [35], [36]. It is located 12-17 degrees temporally and 1.5 degrees inferiorly from central fixation (see Figure 1.5) and its size is approximately 5º horizontally and 7º vertically. The blind spot is not perceived with both eyes open due to an overlap in the visual field of the two eyes.

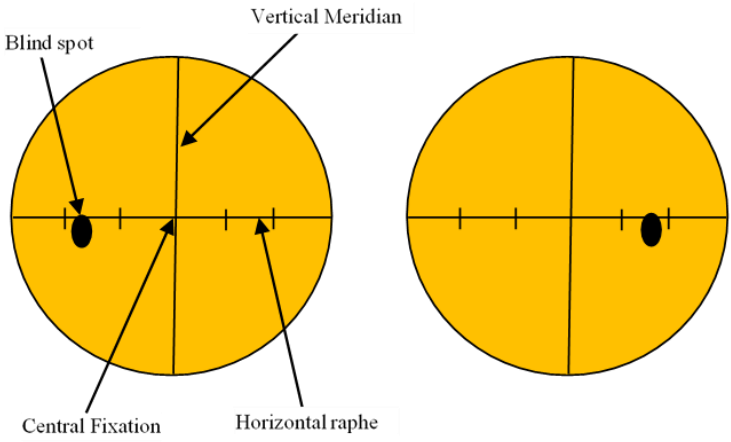


Figure 1.5 Blind spot of left eye and right eye. (Adopted from cehjournal.org)

1.3 Visual Field Test

A visual field test (or perimetry) is a quantitative measurement of visual acuity along the visual field. Each eye is tested separately with the aim of detecting scotomas (areas of depressed or absent vision) as well as more subtle areas of dim vision [37]. As it is a subjective examination, the patient must understand the test instructions and fully cooperate in order to provide a reliable test result [38].

Among the different perimetry methods, the standard automated perimetry (SAP) is most commonly used as a fundamental test for the detection and monitoring of glaucoma [39], [40]. During the test, one eye is occluded, and the other eye should remain fixated at a central light located in the middle of the inside of a sphere (see Figure 1.6). The test is administered by a perimetrist, who monitors the test progress via a screen while the patient performs the test. The most widely used SAP perimeters are Humphrey Field Analyzer (HFA) manufactured by Carl Zeiss Meditec Inc. and Octopus manufactured by Haag-Streit International [41]. These equipment offer a variety of test strategies for screening and diagnosis.



Figure 1.6 A person performing SAP visual field test. A perimetrist monitors the test via a screen to guide the patient. (Source https://www.eyetechtraining.com)

In order to map visual sensitivity at different locations of the visual field, small flashes of light (stimuli) are presented at varying levels of intensity throughout the sphere. The patient is expected to react to each flash light they perceive, by pressing a button. Both Humphrey and Octopus perimeters include screening and quantitative test strategies. Screening test strategies are generally used in normal populations [27]. These tests have shorter duration and are not aimed at determining precise sensitivity values at each location [42]. Instead, suprathreshold stimuli are presented above the estimated detection threshold of a normal visual field location. If the patient responds, it is assumed that the corresponding test location does not have significant loss [43]. A screening visual field test result presents a plot of missed and seen stimuli at each location (see Figure 1.7).

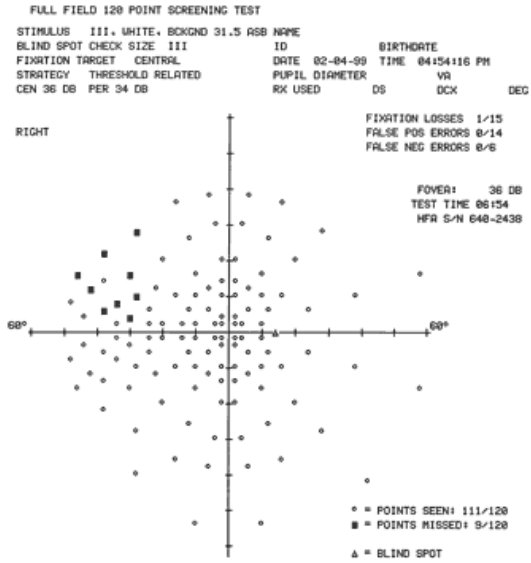


Figure 1.7 Sample suprathreshold screening test result from Humphrey Field Analyzer's full-field 120-point screening test. Seen locations are represented with "o" and missed locations are represented with "■". (Source http://www.oculist.net/)

Threshold test strategies are used for diagnosis to obtain more precise sensitivity thresholds at various locations within the visual field. Sensitivity threshold at a specific location corresponds to the dimmest stimulus intensity that can be detected. These test strategies are commonly used to detect and follow-up pathological visual field defects including glaucoma [44]. For threshold tests, the result is generally presented as a seven-in-one format as shown on Figure 1.8. More detailed information is included on these test results as the aim is to map the visual field more accurately to monitor progress of diseases such as glaucoma.

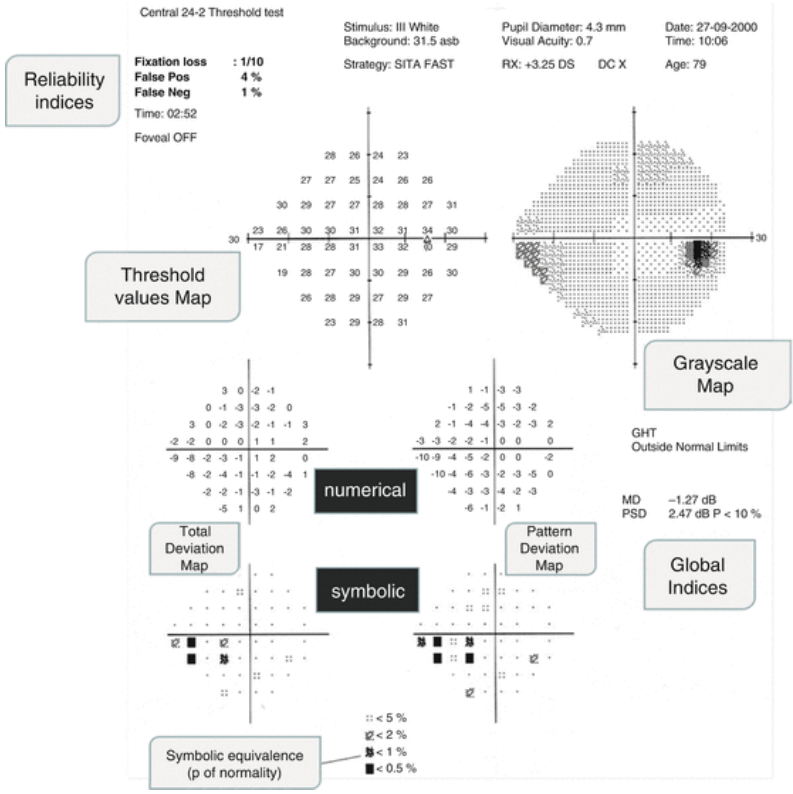


Figure 1.8 Sample threshold visual field test result of a right eye. Reliability indices such as fixation loss, false positives and false negatives indicate the quality of the test. The threshold values map, the numbers at each location grid represent sensitivity values. Total and pattern maps identify significant deviations from normal population of age group. The lower the probability of normality, the darker the box. (Reprinted from [39])

Access to eye care is very restricted in remote areas of low-income countries such as Ethiopia due to scarcity of ophthalmic professionals and diagnostic equipment [45]–[47]. Eye care is not integrated into primary health care and people need to travel long distances to tertiary hospitals in major towns to get access to ophthalmic care, which is not affordable for everyone due to costs related to travel. In countries like Ethiopia, tertiary hospitals organize outreach missions to rural areas with the support of non-governmental organizations(NGOs) to reach out to rural communities [48]. A mission usually lasts for about 10 days and a community gets the chance to a mission once in a year, due to resource limitations. There is a long waiting line during these days and the focus is mainly on cataract which can more easily be

identified. Other cases, including glaucoma, which require more complicated screening tests are not screened for during this missions. Even though both Humphrey and Octopus perimeters include screening test strategies, these devices are expensive and less portable to be used for screening in remote rural areas, especially during field missions.

1.4 Smartphone based visual field testing

The use of mobile devices, including smartphones for medical or public health practices, is referred to as “mobile Health” or “mHealth”. It encompasses a variety of applications including data collection, care delivery, patient communication, use of alternative wireless devices for real-time medication monitoring, and adherence support [49]. Several mHealth interventions have proven its potential in improving health care delivery including eye care [50]–[52].

A number of efforts are going on to introduce an affordable and portable visual field testing technology using smartphones for the early detection of glaucoma. Tsapakis et al. [53] developed a home-based visual field examination method using a PC monitor or virtual reality glasses with an Android smartphone. It allows glaucoma patients to perform a suprathreshold visual field test at home and send the results to a physician. They found a minimum level of difference when comparing their test results to the HFA. Alawa et al. developed MVP FDT, a smartphone based visual field testing tool using a head-mounted display [54]. The Android app implements the test protocols of the Humphrey Zeiss frequency doubling technology (FDT). They found that it produces comparable result to the Humphrey Zeiss FDT device. Paoli et al. developed MyVisualField [55] using a smartphone, a VR headset and a Bluetooth remote for response. There is no information regarding which protocol is implemented by their app. They reported comparable results to conventional perimetry, but mentioned that patients had difficulty using the Bluetooth remote.

While these research studies offer a low-cost and portable visual field test technology based on smartphones, their design and development is mainly focused on the clinical requirement. The authors report on the performance of the tools based on clinical studies conducted in developed countries focusing solely on the accuracy of the results, and do not take into consideration contextual factors that might affect adoption of such technologies in low and middle income countries like Ethiopia.

1.5 Objectives and Research Questions

This doctoral dissertation aims to explore the feasibility of a low-cost and portable visual field screening platform for the early detection of glaucoma, using a smartphone and a virtual reality(VR) headset. To achieve this several research questions have been outlined.

RQ1: What are the needs and preferences of ophthalmic professionals and patients in rural areas of developing countries towards a visual field screening platform using smartphone and VR headset?

This research question aims to identify requirements that are unique to the context of eye care in developing countries. Identifying user needs is critical at the early stage of a user-centered design process, to guarantee usability and usefulness of interactive, technological solutions.

RQ2: How do we design and develop a mobile app for visual field screening tailored to the needs of ophthalmic professionals and patients from rural areas?

This research question addresses technological details including the screening algorithm, display calibration, normative database development and development of the Android app.

RQ3: What are ophthalmic professionals' use and acceptance of a glaucoma screening platform using smartphone and VR headset?

This research question tries to assess to what extent the screening platform is easy to use (usability) and acceptable for ophthalmic professionals in their current setting. This research question is very important, especially in low-income countries like Ethiopia, as VR headsets are not commonly used, let alone for healthcare purposes. Furthermore, the use of mHealth for screening is also not a common practice among health professionals. Therefore,a study of usability and acceptance is a crucial step to guarantee successful adoption of the technology at the end.

RQ4: What is the accuracy of a glaucoma screening platform using smartphone and VR headset compared to a gold standard perimetry equipment?

This research question aims to address clinical accuracy of the platform by comparing its screening results against that of a gold standard perimetry equipment. In order to address research question, a study design where

participants take screening tests with both the platform and gold standard devices and results are compared for agreement, will be followed.

RQ5: What is the sensitivity and specificity of a glaucoma screening platform using smartphone and VR headset?

This research question aims to determine the sensitivity and specificity of the platform. Sensitivity refers to ability a test to correctly identify patients with a disease while specificity refers to the ability of a test to correctly identify people without the disease.

1.6 Methodology

To address most of the research questions, we followed an adopted version of the user-centered design (UCD) framework, proposed by Tariq et al. [56] for mHealth applications targeting rural areas of developing countries. According to Preece et al. [57], UCD is defined as "an approach which views knowledge about users and their involvement in the design process as a central concern". As shown on Figure 1.9, there are four major steps in the UCD process, followed in the work presented in this thesis. First, a user and task analysis is conducted to identify requirements for a visual field screening application. Next, design parameters and devices (smartphone and VR headset) were selected based on the requirements identified. Next, a prototype is developed and evaluated by ophthalmic professionals and patients. Finally, the screening platform is assessed for usability, acceptability and clinical accuracy.

The process followed in this thesis dissertation adhered to the adopted UCD framework for mHealth applications targeting rural areas of developing countries. The context analysis to identify requirements can be found in Chapter 2. Chapter 3 describes the design conceptualization and iterative prototype implementation. Chapter 4 describes assessment of usability and acceptability. Chapter 5 & 6 describe steps undertaken to assess clinical accuracy interms agreement with gold standard and sensitivity and specificity.

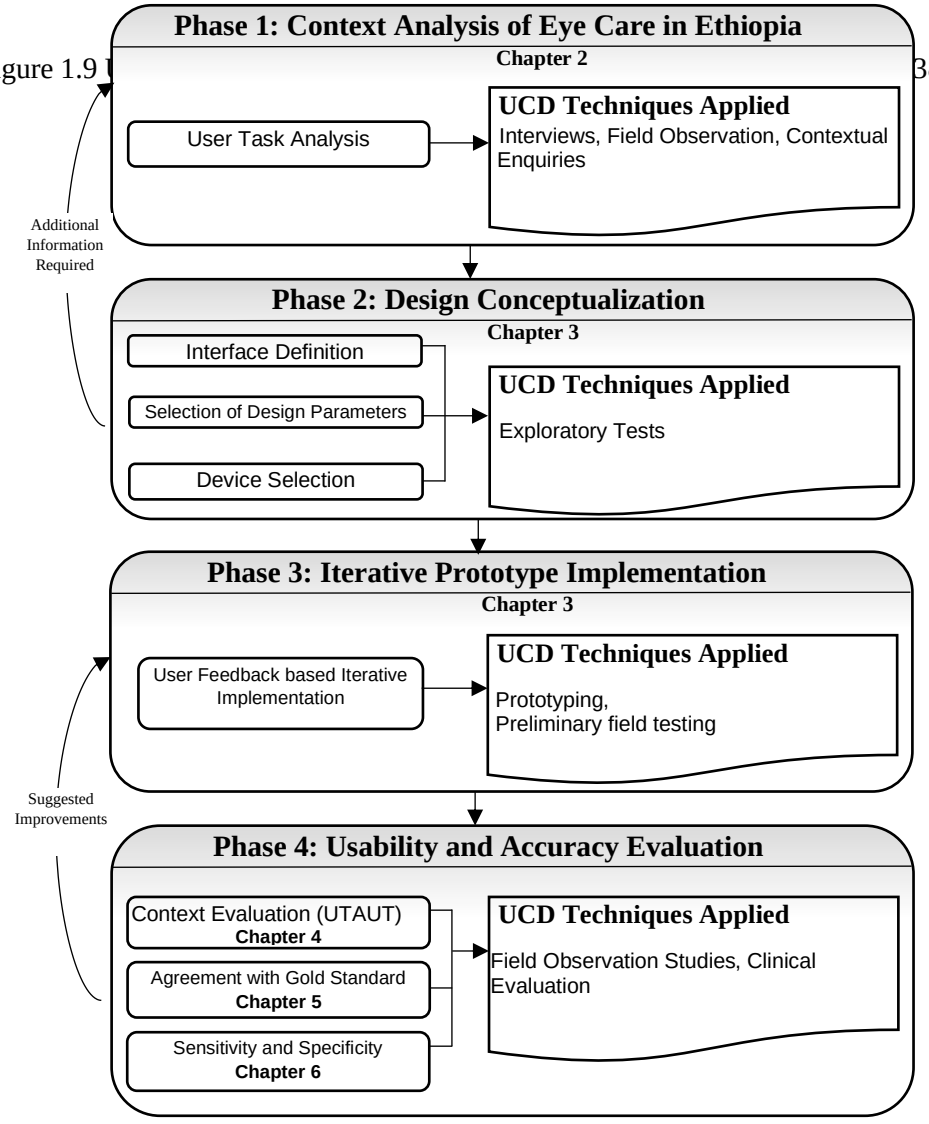


Figure 1.9 [38]

1.7 Thesis Outline

Chapter 2 describes a contextual analysis conducted in selected hospitals in southwest Ethiopia to identify requirements for a visual field screening application. Semi-structured interviews were conducted with ophthalmic professionals to understand how eye care is organized. Field observations were conducted during hospital consultation hours and outreach missions to

elaborate the context of screening and diagnosis of glaucoma. Thematic analysis was carried out according to the method described by Braun and Clarke [58]. Seven themes were identified and illustrated using quotes from ophthalmic professionals(OPs). The themes included, tertiary health care providing primary eye care, outreach missions and the role of NGOs, lack of prevalence data on glaucoma and challenges patients face in performing the visual field test. Three paradoxes were also formulated based on the themes. Key requirements for the design of a visual screening app were identified including such as the need for a short test duration and training feature for patients.

This chapter addresses RQ1: What are the needs and preferences of ophthalmic professionals and patients in rural areas of developing countries towards a visual field screening platform using smartphone and VR headset?

This chapter has been published on EAI Endorsed Transactions on Pervasive Health and Technology Journal: Nida EK, Geurts L, Vanden Abeele V. Paradoxes in Eye Health Care in Low-Income Countries and Design Strategies for Mobile Health Technology to Overcome them. Pervasive Health Technol [59].

Chapter 3 describes the design and development of the screening app. It describes key design decisions taken including selection of an appropriate screening strategy from those available on gold standard devices, selection of headset type and selection of smartphone. The steps followed to calibrate the smartphone display for luminance measurements is also described in this chapter. The chapter finally describes several technical aspects of how the Android application, named Glaucoma Easy Screener (GES), was developed.

This chapter addresses RQ2: How do we design and develop a mobile app for visual field screening tailored to the needs of ophthalmic professionals and patients from rural areas?

Chapter 4 describes a user acceptance study of the visual field screening platform among ophthalmic professionals in Southwest Ethiopia. A pre-post design methodology was adopted to assess OP’s perspective towards using a low cost and portable visual field glaucoma screening platform in their actual settings. OPs from four hospitals filled survey before (pre) and after (post) using the platform on selected glaucoma patients. The Likert-scale survey questionnaire were designed based on the UTAUT framework.

This chapter has been published on the Journal of Medical Internet Research: Formative Research: Nida EK, Bekele S, Geurts L, et al. Acceptance of a Smartphone-Based Visual Field Screening Platform for Glaucoma: Pre-Post Study. JMIR Form Res 2021; 5: e26602 [60].

This chapter addresses RQ3: What are ophthalmic professionals' use and acceptance of a glaucoma screening platform using smartphone and VR headset?

Chapter 5 describes an assessment of agreement between the GES and the GST screening program available on the Octopus gold standard SAP equipment. This chapter also covers how a normative database was built to be used as a reference database for the screening app. Screening test results of healthy participants, who were already recruited for normative database development, were compared between GES and Octopus GST. GST achieved a good level of agreement with Octopus GST. This study was conducted at the ophthalmology department of University Hospital of KU Leuven, Belgium.

Parts of this chapter have been presented as a poster presentation on the EVER 2019: E. K. Nida, E. Vandewalle, K. V. Keer, V. V. Abeele, and L. Geurts, "Clinical validation trial of Glaucoma Easy Screener (GES) as a low-cost and portable visual field screening tool," *Acta Ophthalmol. (Copenh.)*, vol. 97, no. S263, 2019, doi: 10.1111/j.1755-3768.2019.5226.

This chapter addresses RQ4: What is the accuracy of a glaucoma screening platform using smartphone and VR headset compared to a gold standard perimetry equipment?

Chapter 6 describes a study to assess sensitivity and specificity of GES. Healthy participants and glaucoma patients under follow up at the ophthalmology department of Jimma University Medical Center, Ethiopia, were screened with GES. Sensitivity and Specificity of GES was assessed using the ROC curve. A cut-off criteria of 3 missed points as a cut-off point yielded a sensitivity of 90% and specificity of 85%.

This chapter addresses RQ5: What is the sensitivity and specificity of a glaucoma screening platform using smartphone and VR headset?

This chapter is under preparation to be submitted to EAI Endorsed Transactions on Pervasive Health and Technology Journal.

Finally, chapter 7 provides is a concluding chapter with discussion and future work.

Chapter 2

Paradoxes in Eye Health Care in Low-Income Countries and Design Strategies for Mobile Health Technology to Overcome them

This chapter is a copy of the previously published article:

Nida EK, Geurts L, Vanden Abeele V. Paradoxes in Eye Health Care in Low-Income Countries and Design Strategies for Mobile Health Technology to Overcome them. Pervasive Health Technol.

Abstract

OBJECTIVE: To gain a contextualized understanding of eye health care needs, and the challenges and opportunities for designing mobile health solutions for screening of glaucoma.

METHODS: We conducted a qualitative user study at three different healthcare centres in Southwest Ethiopia, including semi-structured interviews with eight eye care health professionals and observations and informal interviews with 125 patients, at three different locations. Interview transcripts were analysed through inductive thematic analysis involving three iterations.

RESULTS: Seven themes were initially identified after two iterations. The themes provided insight into the organization of eye health care and highlighted the challenges faced by eye care professionals and patients. An additional three themes were identified in the third iteration which were formulated as paradoxes: “Money is not an issue, yet there is no money for glaucoma”, “Shortage of eye health care, yet the work is repeated over and over”, “The willing but uncooperative patient tested by the willing but unexperienced nurse”.

CONCLUSION: Findings from this study bear the potential to inspire future designs of mobile health solutions targeting rural communities in Ethiopia and other LICs.

17_Paradoxes in Eye Health Care in Low-Income Countries and Design Strategies for Mobile Health Technology to Overcome them

2.1 Introduction

According to the World Health Organization, 285 million people worldwide suffer from visual impairment, of which 39 million are fully blind [61]. About 80% of the visual impairments are due to curable or preventable causes [62]. Low-income countries(LICs) bear a large proportion of the burden of avoidable blindness [61]. Ethiopia is such a LIC with a high prevalence of visual impairment and blindness [63]. Glaucoma is one of the major causes of irreversible blindness in Ethiopia [64]. According to a national survey in 2006, the disease caused blindness to an estimated 62,000 people [64]. Worldwide, glaucoma is the third major cause of blindness, following cataract and trachoma. With respect to causes of irreversible blindness, glaucoma is the leading cause [65]. Early detection of glaucoma is critical to avoid irreversible blindness [66]. If detected early, further progression of glaucoma can be arrested through anti-glaucoma medication or surgery [65].

Mobile technologies are increasingly being utilized in healthcare in low-income settings, characterized by a limited access to standard diagnostic equipment [67]–[69]. Hence, they provide the potential for the promotion of early glaucoma detection. However, for mobile health technology to be successful, it needs to address the needs of the local population, and deal with challenges which are unique to LICs, such as inadequate infrastructure, low literacy level of health professionals and unsupportive cultural practices [70], [71]. We argue for the design of eye care technologies based on the situated needs of LICs and the systematic inclusion of stakeholders[72].

We present results from a qualitative user study including on-site visits, observations, informal and semi-structured interviews at three different health centre locations in Southwest Ethiopia. Our results provide insight into the organization of eye care in Ethiopia and the needs of the local stakeholders. While the study is situated in Southwest Ethiopia and has a special emphasis on mobile health solutions to aid with the screening of glaucoma, we expose causal mechanisms behind current paradoxes that may typify eye health care in other low-income regions. Furthermore, this work may also contribute to the design of future pervasive healthcare solutions, by highlighting design opportunities to overcome these paradoxes.

2.2 Related Work

2.2.1 Glaucoma and Eye Healthcare in Ethiopia

As discussed in Chapter 1, glaucoma is an umbrella term for a group of diseases that lead to progressive damage to the optic nerve. It is commonly caused by fluid that builds up in the front part of the eye, increasing the internal pressure and subsequently damaging the optic nerve [73]. Vision loss due to glaucoma initially occurs at the peripheral field of vision and gradually advances to the central vision. Patients are not aware of the condition until there is a significant vision loss, which is why it is also referred to as "the silent thief of sight" [74].

Unfortunately, people in rural areas of Ethiopia need to travel long distances to larger urban centres to gain access to eye care [75]. Similar to healthcare systems in several other countries, the Ethiopian system is organized into three tiers (see Figure 2.1). The primary level aims to deliver local care. The secondary level entails the care provided by medical specialists. Finally, the tertiary level involves specialized hospital care [76].

However, the population per Ethiopian healthcare facility is three times higher than even the sub-Saharan average; indicating a tremendously more challenged infrastructure compared to high income countries [77]. There is also a significant shortage of health professionals in the health system. In the year 2002, the ophthalmologists to population ratio in Ethiopia was one ophthalmologist per million people, with more than 70% of them working in Addis Ababa, the capital [75]. This low prevalence of eye health care professionals stands in sharp contrast with the prevalence of eye diseases, which are even more concentrated in rural areas [63].

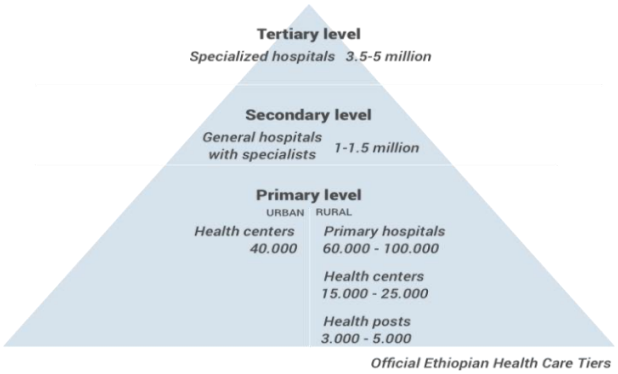


Figure 2.1. Health Tier System of Ethiopia (Health Sector Development Program IV] [78])

Given the asymptomatic nature of glaucoma and the lack of access, most patients from rural areas visit eye care centres only once they experience a palpable loss of vision[79]. Such patients with advanced glaucoma face difficulty in various activities like reading, noticing objects in their peripheral vision and adapting to different levels of lighting [80]. Besides vision loss, the resulting dependence on others, diagnostic concerns as well as the costs and potential side effects associated with treatments often negatively impact quality of life [81].

2.2.2 Screening tests and technologies

To screen for glaucoma, three tests are performed [66] as discussed in Chapter 1. First, intra-ocular pressure is measured using a tonometer. Second, the optic disc is inspected using an ophthalmoscope. Finally, the visual field is inspected to check for areas of vision loss, mostly using standard automated perimetry (SAP) equipment [82]. Referral decisions for further diagnosis of glaucoma are based on the combined results of these three tests [66].

Handheld and portable versions of both tonometer and ophthalmoscope are widespread in Ethiopia, and used for community screening in situations where standard hospital-based instrument are not available [83]. These instruments operate without electricity, making them well suited for screening, even in remote rural areas where there is limited or no access to electricity. However, for visual field testing (VFT), such an electricity independent, portable instrument is not yet available.

2.2.3 Mobile health technologies and screenings

The availability of wireless communication with mobile devices in LICs has leapfrogged conventional landline systems [84]. The use cases of feature phones and smartphone applications in health care include patient assessment and education, physician reference and education, photographic and image processing and patient record keeping. For instance, there are a number of mobile applications for visual acuity testing that can be used in situations where other tests of visual acuity are not readily available [85]. Smartphones are also being utilized for retina imaging with an indirect lens and the built-in

camera [86]. Assessment of refraction with a pinhole adopter attached to a smartphone is also another example to mention [87].

2.3 Method

We conducted a qualitative user study at three different healthcare centres in Southwest Ethiopia, with the main aim of gaining a contextualized understanding of eye health care needs, and the challenges and opportunities for designing mobile health solutions for screening of glaucoma. To this end, we carried out semi-structured interviews with health professionals, as well as informal interviews and observations with patients. Focus was given to health professionals since they will be primary users of the system in the future. Questions in the semi-structured interviews centred on gaining knowledge about the current practices of glaucoma screening and diagnosis. Following patient registration, screening, and diagnosis allowed us to observe different contexts during consultation hours as well as during an outreach mission, an organized field trip of eye healthcare workers to rural areas.

2.3.1 Duration and Location

During July and August 2017, we collected data in three locations in Southwest Ethiopia (see Figure **2.2**). Jimma University Medical Center (JUMC) is a hospital located in the city of Jimma, 350 km southwest of the capital Addis Ababa, in the Oromia regional state. Seka Chokorsa Primary Hospital (SCPH) is part of the small town of Seka, 23 km from Jimma, also in the Oromia regional state. Finally, Saja Primary Hospital (SaPH) sits in in the town of Saja, about 110 km on the main road from Jimma to Addis Ababa, in the 'Southern Nations, Nationalities and Peoples' regional state.



Figure 2.2. Locations of hospitals included in the study. Saja is 240 km Southwest of Addis Ababa, Jimma is 350 km Southwest of Addis Ababa and Seka is 373 km Southwest of Addis Ababa.

2.3.2 Participants

The eight participants we observed (see Table 2.1 Overview of participants in the semi-structured interviews.) included two ophthalmologists, three ophthalmic nurses and three integrated eye care worker (IECW) nurses. IECW nurses are general nurses who received a short training on the treatment of trachoma trichiasis (TT), a disease caused by an infection resulting in inflammation and scarring of the surface of the eye [88]. We recruited participants through snowball sampling, a technique where each participant suggests further potential interview partners [89]. All semi-structured interviews happened on site and in a one-on-one setting, except one interview which was conducted with two IECW nurses at the same time. In addition to the semi-structured interviews, we informally conversed with patients. At JUMC, we observed the diagnosis of about ten glaucoma patients. During the outreach mission at SaPH we encountered 115 patients, screened over two days.

Table 2.1 Overview of participants in the semi-structured interviews.

Center		Occupation
Jimma University Medical Center (JUMC)	P1	Ophthalmologist
	P2	Ophthalmologist
	P3	Outreach Coordinator
	P4	Ophthalmic Nurse
Saja Primary Hospital (SaPH)	P5	Ophthalmic Nurse
	P6	IECW Nurse
Seka Chokorsa Primary Hospital (SCPH)	P7	IECW Nurse
	P8	IECW Nurse

2.3.3 Data Analysis

All interviews and observations were conducted by the first author of the paper. All interviews were audio-recorded and transcribed immediately. Next, a thematic analysis was carried out involving two additional researchers. according to an inductive thematic analysis process [58]. No a priori lenses or theories were established, but rather themes were identified via the data. In a first iteration, in vivo coding was applied by each researcher individually to generate initial codes after familiarizing with the data. In a second iteration, initial codes were revisited and searched for themes describing trends. Codes were clustered into concepts, and core concepts were defined for each cluster via the affinity diagramming technique [90]. In a final iteration, themes were revisited and three additional themes, which were formulated as paradoxes, were added.

2.4 Results

We have identified seven themes in our thematic analysis. These provide insights in the organization of eye healthcare and the needs of local stakeholders.

I1 : Tertiary health care to provide primary eye health care

Our first theme concerns the provision of healthcare according to the different layers of primary, secondary and tertiary care. We found that eye care beyond treating infections and TT is not well integrated into the primary level of healthcare. Hospitals and health centers lack the necessary equipment and ophthalmic professionals to provide basic eye care services. As a consequence, patients who need eye care are required to travel to a more distant and less accessible specialized hospital. Not all patients can afford to travel such distances. Therefore, sometimes, primary hospitals prescribe medication for glaucoma without a proper diagnosis.

Observations. SCPH, as a primary hospital, is expected to serve up to 100.000 patients. Despite the high prevalence of eye diseases, we found there neither a dedicated room, nor a specifically educated eye care professional besides two IECW nurses. These provide treatment for patients with TT on site, in addition to their regular duties. A patient with any other eye problem is referred to JUMC, even when it is known that patients will not be able to do so. The nurses consider glaucoma to be beyond their expertise as they lack the necessary training and equipment.

P7: We take the history and visual acuity. If it is an infection, we give them antibiotics. If we see TT, we do surgery for them. But if it is cataract, we refer them to Jimma. But some of them don't go to Jimma because they cannot afford it.

SaPH serves a similar number of patients as SCPH. Here, among the two nurses one is specialised on ophthalmology. A small room serves as an eye unit; however, it is poorly equipped. Besides a Snellen chart to test visual acuity, the room contains one handheld tonometer to measure the intraocular pressure (IOP) and a torch light, used as an ophthalmoscope(see Figure 2.3).



Figure 2.3: An ophthalmic nurse measuring intra-ocular pressure (left) and screening the optic disc, using torch light (middle) and a handheld ophthalmoscope (right).

The medical staff has no other instruments to further eye examinations available. Similar to SCPH, beyond eye allergies and infections curable with medication, TT is the only eye condition that can be treated at this hospital. For most other eye diseases including glaucoma, patients are referred to JUMC.

P5: We first take visual acuity. We may also take tension (IOP) based on the symptoms. The main test to lead us for further is visual acuity. [..]
I: How do you detect glaucoma here?
P5: Mostly it is clinical. If they complain about pain, we suspect glaucoma then we take tension (IOP). If the tension is above normal, we immediately

refer them to Jimma. If they cannot afford to go to Jimma, we start medication for them here.

JUMC is the only specialized tertiary hospital for the entire region of Southwest Ethiopia, serving more than 4 million people. The hospital has a well-established eye unit with its own separate building and staff: three ophthalmologists, 13 ophthalmology residents, five optometrists, two ophthalmic nurses, two cataract surgeons and one refractionist. Compared to primary hospitals, the unit is comparatively well equipped with medical equipment such as a slit lamp, a biomicroscope, a laser capsulotomy and a VFT device.

Patients travel to JUMC from areas as far as 450 km, across the border with South Sudan. Patients start queueing up in the waiting area of the unit around 5AM, although service only starts around 8AM. Given the large number of patients showing up each day, the unit limits the daily intake. Some patients end up waiting three or more days before they are seen. Despite the fact that it is a tertiary care hospital, it often acts as a primary care contact point for many of the patients.



Figure 2.4: Left: Morning scene in the JUMC waiting room. Right: Other patients, outside the waiting room, unable to enter the overcrowded waiting room.

At the eye unit of JUMC, all new patients first go through basic screening tests. Patients with a suspected glaucoma take the visual field test using frequency doubling technology (FDT) perimetry equipment. This a specialized but expensive medical device; however, even though it once comprised a gold standard, it has become obsolete in modern Western hospitals [91]. HFA, which is more accurate than the FDT, and currently considered the state of the art for visual field testing (and hence glaucoma diagnosis), is only available at a private clinic in the city of Jimma. Most

patients visiting the eye unit of JUMC cannot afford to pay for private service, which is far more expensive than public health institutions. There is only one FDT device at this hospital, and there is no other public hospital in the Southwest where visual field-testing equipment is available.

Outreach programs and NGOs

This theme concerns the role of NGO's in the delivery of eye care. NGO's play a vital role in the effort to make eye care more accessible to rural communities by organizing and funding the outreach program of JUMC. Furthermore, they provide training to regular nurses on basic ophthalmic care, such as the treatment of TT.

Observations. The eye unit of JUMC, in collaboration with an NGO, organizes outreach missions to selected primary hospitals and health centres in the Southwest region to offer additional coverage of health services. As such initiatives depend, for example, on the current weather or the generosity of potential donors, they do not follow a consistent schedule . Yet, an average of seven missions can be realised each year. The main focus of these missions is cataract surgery, but other simple eye diseases are also treated on site. During outreach programs, test results are neither recorded nor printed out for further consultation.

On one such mission we observed at SaPH in August 2017, more than 115 patients were screened and, if necessary, received cataract surgery right away (see Figure 2.5). Every patient went through basic screening that involved simple tools such as torch light, a handheld ophthalmoscope, and a handheld tonometer. The screening tests take about ten minutes per patient with the aim to identify patients with cataracts, who require on-site surgery. For simpler health issues, such as infections, patients received medicine prescriptions, though for most conditions, including glaucoma, patients were advised to seek treatment at JUMC.



Figure 2.5. Outreach mission at Saja Primary Hospital. Patients waiting for screening(Left). Patients waiting to go through cataract surgery(Right).

Non-Governmental Organizations (NGOs) play a significant role in the organisation as well as the financing of outreach missions. For instance, the outreach program of JUMC is financed by the NGO "Light for the world". Another NGO, "Orbis International", is involved in the national "trachoma eradication" program [92] and has organized trainings for general nurses, focusing mainly on trachoma.

P6: "Every week on Wednesday and Thursday we move to more rural community households to conduct door-to-door eye exams. We mainly focus on trachoma."
I: Do you do this on a regular basis?
P6: "Yes, we are being supported by the NGO Orbis."

Both patients and health workers highly depend on the NGOs to fund and organize eye care. Health care workers are also expected to report to the funding NGO.

P6: We were mainly trained for trachoma. […] We report quarterly to our donor and region office on the cases we have treated and referred.

The confidence in the NGO driven primary healthcare through outreach programs is high, to such an extent that the nurses we interviewed do not consider cost to be a critical factor for a portable glaucoma screening tool. They suggested NGOs will cover the expenses of such equipment.

I: Do you think a tool including the smartphone, VR headset and the remote would be affordable for your institution?
P6: "I think it is well affordable. Moreover, in addition to our hospital, NGOs can help us on this."

I: If there would have been a portable VFT tool, do you think visual field will also be taken during outreach?
P5: This depends on the objective of the campaign. Since the main objective of

> *our outreach campaign is glaucoma screening, it would be done for sure. But the funding of this outreach is specifically for cataract. […] The donors may not be happy if we don't focus on cataract.*

Glaucoma is too invisible to be a priority

This theme concerns the relatively lower priority given to glaucoma compared to other eye diseases. This is mainly due to lack of more accurate prevalence data and asymptomatic nature of the disease. Other eye diseases such as cataracts and TT get higher priority both from the government and NGO's..

Observations. Glaucoma is currently not considered a major health problem. Other eye diseases are given a higher priority by the government and NGOs. In particular, TT has been the main focus of the IECW nurses in the primary hospitals. According to a national survey in 2006, the condition is the second cause of blindness in the country [63]. Moreover, different from glaucoma, symptoms are highly visible and easily identified with a torch light. Cataract is another eye condition slowly gaining attention in the primary hospitals, next to TT. Cataracts are also easily identifiable, compared to glaucoma. While not available through primary hospitals, outreach missions provide treatment to patients.

> *P7: "The major focus is now on TT. There is a national program to eradicate TT. While we work on TT, we started to encounter cataract cases as well. Now, cataract is also becoming an issue of discussion. But we never hear anything regarding glaucoma. Maybe it could be a focus in the future after TT and cataracts?"*

However, according to ophthalmologists and ophthalmic nurses at JUMC, glaucoma is a very common condition among their patients. They believe it to be under-diagnosed and voiced frustration on the lack of interest from government and NGOs for this 'invisible disease'.

> *P4: "Glaucoma is the least diagnosed disease in Ethiopia. There are a lot of cases that are missed. Some patients come here (at JUMC) complaining of other simple symptoms. But when we examine them, they already have advanced level of glaucoma. I have seen a patient with an IOP of 80."*

> *P2: "Glaucoma is very common case among patients in our clinic (JUMC). I don't think that the survey done some years ago, which is available online, reflects the real situation."*

Lack of prevalence data

This theme concerns the lack of data on prevalence of eye diseases. The single most recent prevalence data on eye diseases in Ethiopia is from a national survey back in 2006. Ophthalmologists insist that eye disease such as glaucoma are actually more prevalent than what is reported in the survey.

Observations. In line with the lesser attention for 'invisible' eye diseases, data with respect to the prevalence rate of glaucoma in Southwest Ethiopia is similarly barely available. A national survey from 2006 puts glaucoma as the fifth major cause of blindness in Ethiopia [63]. However, the ophthalmologists we interviewed disagree with this number, and insist that based on the cases they encounter daily, glaucoma should be ranked higher. Unfortunately, there is no systematic way to collect data on the prevalence of various eye conditions.

However, at primary hospitals of SaPH and SCPH, the staff register all the cases on a form. Typically, they record the date, age, sex, condition and other details for each case. They use the record mainly for reporting purposes at the end of every month to NGOs. During outreach missions, Jimma university staff tallies each case identified by screening on a paper form, one for each day. Data is summarized by counting the tallied forms of all days at the end of the mission (see Figure **2.6**). This process is entirely paper-based.

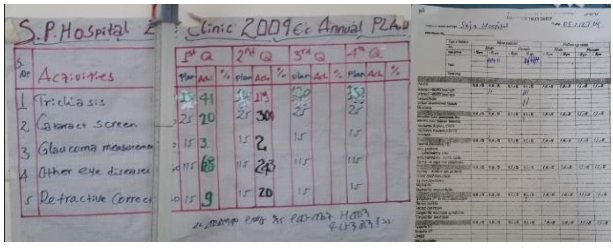


Figure 2.6. Paper forms for recording and reporting the number of different types of eye diseases.

Problematic patient data storage and retrieval

This theme concerns the current practices of patient record keeping and retrieval. Every patient information is kept in papers with a blue folder for

each patient holding medical history including results of previous tests. Retrieving patient records for subsequent visits is a challenge to the extent where records of patients are missing.

Observations. In the hospitals we visited, there is no electronic medical record system; patient records are entirely paper-based. During outreach missions, patients show up for screening without registration. The screening results are not recorded. For diseases not treated at the site, patients are orally advised to go to JUMC. When patients are referred from a primary hospital like SaPH or SCPH to a tertiary hospital like JUMC, they are given a referral paper form, which is filled out by the referring institution with a summary of the medical details. The patient's folder is not exchanged between institutions.

> *I: When you refer to Jimma, what do you send with the patient? Do you include your test results?*
> *P5: No, we just write a note that we suspect glaucoma. We don't send the results. We just send them with the standard referral form. Some patients come back from Jimma and tell us the medication they received from Jimma. Some don't come back, so we cannot follow them.*

Upon registration at JUMC, every patient is assigned a new patient folder including details on name, age and address as well as their medical history and all test results (see Figure **2.7**).

In the Ethiopian health care system, there is no social security provision that provides all patients with a unique identifiable number. Unfortunately, people from rural areas and older people often do not know their birth date and have an informal naming system. As a result, any system that identifies and retrieves patient records on a combination of name, birthdate or social security number is impossible. Hence, JMCU provides patients with a small paper card containing a unique identification number specific to the eye unit.

One of the major challenges with this paper-based patient record keeping system is retrieving patient folders during subsequent visits. Patients have to present the ID card to the reception so that their folders can be retrieved. Some patients lose the small card, making it difficult for the reception to locate their folders. But sometimes, even if the patient brings the ID card, folders can be missing. During our visit at JUMC, we witnessed a glaucoma patient whose

medical record was not found, including results of three visual field tests taken previously.



Figure 2.7 A blue folder holding patient records (Left).Patient folders on shelves behind the reception desk of the eye unit of JUMC (Right).

Manual copying of test results

This theme concerns the challenges ophthalmic nurses face in administering visual field tests using the FDT at JUMC. As the equipment had ran out of print paper, nurses are supposed to manually write down test results wasting more time and effort.

Observations. The FDT visual field test equipment at JUMC produces test results that can theoretically be printed. However, during our visit, the printer was out of order. The nurses told us it ran out of paper a long time ago. To store test results, they are copied manually from the device's screen on a paper form prepared for this purpose (see Figure 8). Ophthalmic professionals administering the visual field test spend much time and effort documenting results.

Power interruptions, which happen multiple times each day, are another challenge. Because the FDT equipment is not capable of saving intermediate test results, the entire test has to be repeated if power goes down before the test is completed and results have been copied onto paper. This is a constant worry of eye healthcare workers and another reason why tests results are copied as quickly as possible on paper–a practice that is prone to errors.

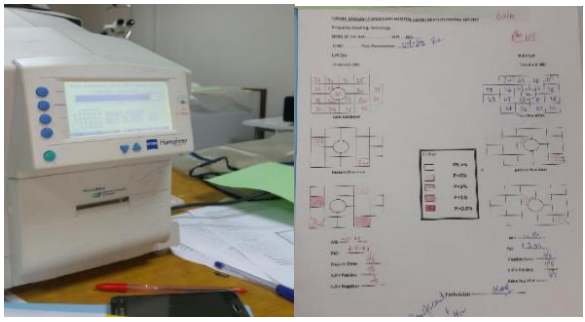


Figure 2.8. Various details of a test result are copied from the FDT screen to a paper form.

Visual Field Testing is challenging for patients and nurses

The last theme concerns patient related challenges ophthalmic nurses face in administering visual field test with FDT. As many of the patients performing the test are older adults from rural areas with little or no exposure to technology, more time and effort is spent in training the patients and repeating unsuccessful tests. As a consequence of this challenge, ophthalmic nurses consider it as a 'boring' task and tend to avoid it or at least delay it as much as possible.

Observations. At JUMC, a patient suspected of glaucoma based on basic screening tests (measuring IOP and inspection of the optic disc), may take the visual field test. During the test, stimuli appear at various locations of the visual field. The patient is expected to look at a fixation target at the centre of vision, for the entire duration of the test and to press a response button every time a stimulus is presented (see Figure **2.9**) in the periphery. After a series of stimuli, the equipment compares the response pattern of the patient with a normative database to regions in the periphery with vision loss. The test is done separately for each eye [93].



Figure 2.9. Patients with the response button during a visual field test with FDT.

Patient training is considered to be critical for the success of the test. A detailed explanation is given for those patients taking it for the first time. A leaflet from equipment manufacturer shows the fixation target and stimuli; nurses use it to prepare patients for the test (see Figure **2.10**). In addition to the explanation by the ophthalmic professional, a demo test familiarizes patients with the test scene and response button, before the actual test begins.

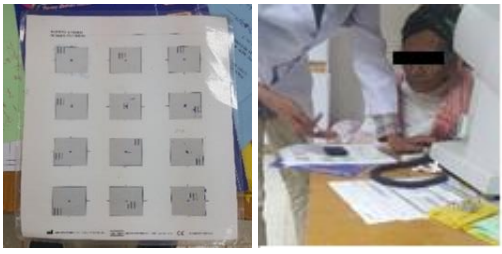


Figure 2.10. Left: FDT training manual with an illustration of stimuli. Right: An ophthalmic nurse is giving an explanation to a patient, using the manual.

The equipment relies on the age of the patient to determine the intensity of the stimulus presented, and to compare the results with a normative database. Most of the patients taking this test at JUMC are older adults from rural areas. Often they do not know their exact birth date, and cannot provide accurate age information which may affect the reliability of results. Furthermore, patients with an advanced level of glaucoma have damage in their central vision and are unable to fixate during the test. In the most advanced cases, patients are not be able to complete the test with their visual field results reported as, “cannot fixate”.

P_4: “For some patients we simply write “The patient cannot fixate”. So, they won’t have any FDT results.”

Another challenge for older adults from rural areas is a lack of familiarity with technology. Understanding the visual field test procedure is difficult for them, especially during their first attempt. For most patients from rural areas, pressing the response button can by itself constitute a challenge.

Furthermore, patients highly respect physicians and are afraid of making mistakes. As one of the ophthalmic nurses mentioned, patients from rural areas consider medical professionals "next to God" and try to be as cooperative as possible. Because of this desire to please test examiners and the associated internalised shame, they might avoid reporting their difficulties during the visual field test. As a consequence, the test typically has to be repeated a number of times before a reliable outcome can be obtained. The entire testing session can take from 30 minutes up to more than an hour for some patients.

Given the challenges they encounter, particularly with older patients from rural areas, the ophthalmic nurses consider the test boring and tiresome work. Consequently, visual field tests are avoided in the morning, which are considered the busiest hours. Patients in need of VFT are scheduled for Friday, or in the afternoon. Both ophthalmic nurses we interviewed mentioned that they administer only three to five visual field tests per week. Moreover, to our surprise, we observed that the VFT room was closed during most of our visits, including Fridays.

2.5 Discussion

The themes that emerged from thematic analysis of the data contained pertinent information on the context of eye care in Southwest Ethiopia. They provided more insight into the organization of healthcare ,identified key stakeholders in the delivery of eye care, explained current practices in the screening and diagnosis of glaucoma and highlighted challenges faced by ophthalmic professionals and patients.

Upon further analysing the aforementioned themes, we were confronted with paradoxes – dynamics where apparently contradictory elements are interrelated to produce an unanticipated result. In the following paragraphs we detail these paradoxes, shed light on the causal mechanisms and suggest design opportunities for mobile health technologies addressing them.

Paradox 1: Money is not an issue, yet there is no money for glaucoma

We found both patients and health workers to be highly dependent on the NGOs to fund and organize eye care. Given the frequency and the reliability of NGO-organized and funded (outreach) programs, and the collaboration with national government, it can be argued that NGOs are an established part of primary and tertiary care. This is in line with other studies who described the important role of NGOs in the health sector in LICs [94].

The confidence in NGO driven primary healthcare is high, to such an extent that the nurses and doctors we interviewed did not consider cost to be a critical factor for a portable glaucoma screening tool. If the value of such a tool can be made 'tangible', they claim NGOs will cover the expenses.

However, eye care professionals pointed out that NGOs (in agreement with national government) define what gets funded, and that the current focus is on TT and Cataract, not on glaucoma. Eye care workers are also expected to report the number of cases of TT and Cataract treated to the NGOs and government. Health care programs are driven by impact, and governments as well need figures on prevalence and ailments. Detrimental impact of diseases as well as the positive impact through campaigns need to be made tangible [95]. Glaucoma is currently not 'visible'. Despite the conviction of the ophthalmologists that it is highly prevalent and detrimental.

Hence, *design opportunities* for mobile eye health care solutions could consider features that enhance 'visibility of impact' such as storing the times it was used, documenting the number of healthcare centers where it was used, recording the number of patients helped, etc.

We also witnessed issues surrounding the base data tests are conducted on. The FDT test results are compared to a normative dataset from Western patients, despite the fact that the prevalence of Glaucoma is higher on the African continent, and African patients may differ in progress of the condition [96]. Despite the lack of representation, these normative datasets are specific to a given piece of equipment and cannot be reused on a different equipment with different parameters [26].

Hence, *design opportunities* for mobile eye health care solutions lie in screening tests that require reference database of normal subjects, such as the VFT screening. Researchers and designers could investigate how to collect and store results with the aim to build localised reference datasets.

Paradox 2: Shortage of eye health care, yet the work is repeated over and over

The ophthalmologists-to-population ratio in Ethiopia is one per million people [75], in sharp contrast with the high prevalence of eye diseases. Based on our interviews and observations, no ophthalmologist doctor can diagnose and perform surgery in any other hospital in the Southwest of Ethiopia, except at JUMC. As a consequence, patients need to travel long distances, in difficult circumstances, and wait sometimes up to three (3!) days for an initial consultation.

Despite this shortage in eye health care professionals, we observed many inefficient work practices. A first loss in efficiency is rooted in the combination of a paper-based record system and the absence of a national social security or citizen identification program. Consequently, each health institution maintains its own paper-based patient record, and patients (also illiterate patients from rural areas) are responsible for retaining their unique identifier number, printed on a small paper slip. This results in a broken information flow, i.e. a lack exchange of patient data among hospitals. Results from earlier tests at other hospitals or during outreach missions are not (re-)used. Moreover, patients lose their ID card or paper folders are misplaced and no longer found.

Patient data exchange is generally challenging–even in high-income countries [97]. Given the absence of electronic health records and national patient identification, mobile health solutions cannot take advantage of linking data to existing electronic health records.

The design of the visual field-testing equipment itself is also a cause of superfluous work. Power outages and unsteady access to internet, in combination with a device that cannot save intermediate results, lead to visual field tests having to be performed repeatedly. Moreover, an unpredictable supply of print paper complicates printer usage. Hence, test results are manually copied from the device's screen onto a paper form. As a result, ophthalmic nurses find VFT a lengthy, tedious job. While it is essential for diagnosis, we witnessed it was avoided as much as possible. The fact that eye health professionals would rather rely on other inferior tests for the diagnosis

of glaucoma, is a practical example of how technology can end up being under-utilized if not designed to fit in to the actual context [98].

The finding of unreliable IT infrastructure may contrast with the high rate of penetration of mobile phones and rapid expansion in coverage of the underlying network infrastructure in LICs [99]. We did find that, most of the time, ICT is up and running in rural Ethiopia. However, we also found short moments of power outages are frequent, which affects the stationary equipment in hospitals more than personal mobile devices.

Hence, *design opportunities* for mobile eye health care solutions could lie in the combination of taking advantage of the presence of ICT infrastructure, without being stymied by the frequent glitches. They should be able to continue to work in periods of temporary downtime of communication networks, i.e. through implementations of good syncing protocols as well as online and offline modes. Furthermore, they should be able to work in periods without electricity, i.e. by battery management and power- and back up strategies and avoid relying on third party logistics, such as printers, copiers, etc.

Paradox 3: The willing but uncooperative patient tested by the willing but unexperienced nurse

As a final paradox, we found that the patients and nurses themselves also pose a particular challenge. First, for many health solutions, similar to VFT, participation from the patient is indispensable. Therefore, the patient needs a clear understanding of the test and what they need to do, to obtain a reliable result. As seen from the experience with the FDT at JUMC, old patients from rural areas have difficulties in understanding the test, mainly due to lack of familiarity with technology. If a portable visual field screening tool is to be used in situations like the outreach mission, this issue is even more pronounced.

Hence, *design opportunities* for mobile eye health care solutions are in the field of on boarding and training so that patients can gain experience with tests before taking them, e.g. through a tutorial or entry level. They should also be accompanied by instructive materials or demos, that make the explanation of the test easier for patients, e.g. manuals, demonstrations, etc.

Due to high respect for medical doctors and social desirability, patients do not dare to freely share problems or discomfort. This lack in straightforward communication can result in skewed or unusable test results.

Hence, *design opportunities* for mobile eye health care solutions could allow test examiners to closely monitor the patient's performance, instead of having to rely on their verbalisations. Examiners should also be given access to intermediate test results to check and easily abort and restart tests if necessary.

2.6 Conclusion

We presented a qualitative analysis of the organization of eye care in Southwest Ethiopia, mainly focusing on screening for glaucoma. Through an inductive thematic analysis on the basis of semi-structured interviews and observations made at three different hospitals, we have been able to highlight the challenges faced by ophthalmic professionals and patients, and identified paradoxes in the practice of eye care that present design opportunities. Our findings bear the potential to inspire future designs of mobile health solutions targeting rural communities in Ethiopia and other LICs.

Acknowledgements.

The authors thank the department of Ophthalmology of Jimma University for their support during data collection. We also thank all the participants for dedicating their valuable time to the interviews and observations.

Chapter 3

Design and Development of Glaucoma Easy Screener

Abstract

Objective: To design and develop a visual field screening Android App.
Methods: Smartphone display was calibrated for accurate luminance control and appropriate visual field screening test strategy was adopted from gold standard device.
Results: An android app (GES) was developed based on the display luminance parameters and adopted screening test strategy.

3.1 Introduction

Glaucoma Easy Screener (GES) is intended to be used as a low-cost and portable alternative kit for performing visual field tests, to detect glaucomatous visual field defects. Such a tool can help health professionals in remote areas to screen for the disease and refer suspected patients to hospitals for further diagnosis. GES comprises of a Moto G5 smartphone with a 5-inch LCD display, a Homido v1 VR headset and a Logitech gaming joystick with a USB connection to the smartphone. Moto G5 was selected for its relatively affordable price and wide range of screen luminance values. Homido v1 VR headset was selected for its relatively lower cost (around 70 euro) and an adjustable tight fitting head strap that prevents dislocation of the headset by head movements (see Figure 3.1).

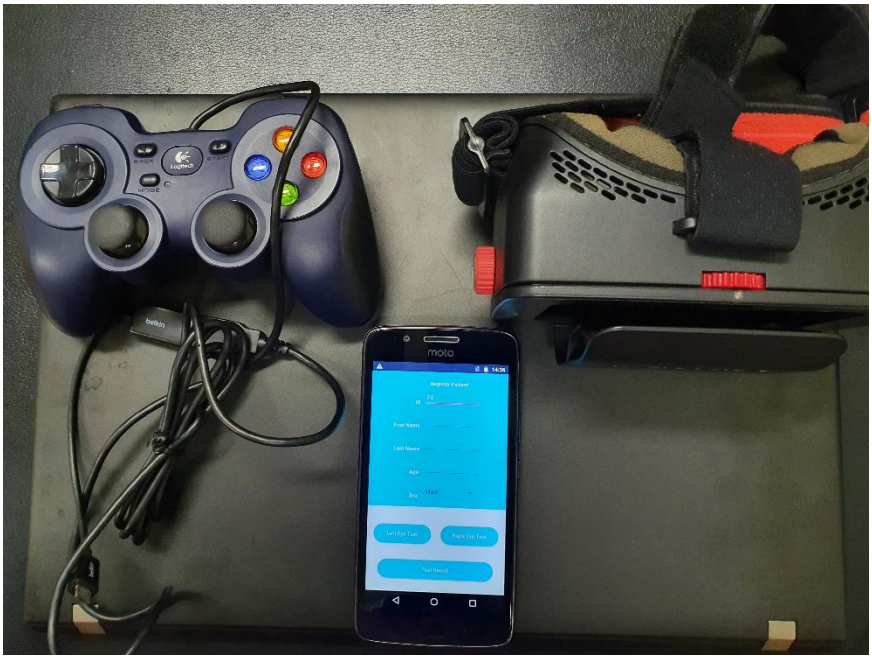


Figure 3.1: The three components of GES: smartphone, virtual reality headset and joystick.

As already discussed in Chapter 1, visual field-testing maps visual sensitivity at different locations of the visual field, by presenting small flashes of light (stimuli) at varying levels of intensity. The patient is expected to react to each flash light as they perceive, by pressing a button, while maintaining gaze fixation at a central point.

There are functional and technical requirements that should be addressed by any visual field test technology [100]. A major functional requirement that should be maintained is having accurate control over luminance of the background and stimuli. Background luminance should remain constant throughout the test while luminance of stimuli is manipulated according to the test strategy selected. Next to luminance control, there is a technical requirement to incorporate reliability indices to assess the reliability of the test result. These include fixation loss rate, false positive rate and false negative rate, as will be explained later in this chapter. These indices are presented along the test result to help the physician determine the reliability of the test. Furthermore, for screening tests there should be a reference database of normal eyes (normative database).

Besides the functional and technical requirements, additional contextual requirements were identified from a contextual inquiry of eye care in low-income countries, as presented in the previous chapter. These include: the need for quick screening tests, with a short test duration of maximum 5 minutes for both eyes, the need for a feature to train patients on how to perform the test, the need for a mechanism to track test progress, the need for the platform to be portable, low-cost and easy to use.

This chapter presents the technical details of the design and development of the screening application. First, the screening strategy adopted is described. Then the smartphone display calibration procedure is described. This is followed by a detailed description of test parameters including stimulus size, stimulus duration, response time and reliability indices. Following this, development of normative database is described. Finally, development of the Android application and test procedure are briefly described.

3.2 Screening Test Strategy

Designing a new visual field screening test requires significant effort including its clinical validation, so we decided to adopt an existing screening program on SAP equipment. After an assessment of screening programs available on SAP equipment in collaboration with glaucoma experts, the glaucoma screening test (GST) recently introduced in the Octopus perimeters (Haag-Streit AG, Köniz, Switzerland) designed for performing quick visual field screening, was found to be the most appropriate [101]. The test takes less than a minute for normal participants and up to 1.5 minutes for patients with

advanced glaucoma [102]. The test comprises of 28 locations in the central 30^0 as shown on Figure 3.2 [103]. The intensity of the stimuli for this screening test are set at a level equal to the 95^{th} percentile of the normal population [103]. If a stimulus is seen in the first presentation, the point is designated as normal (represented by "+" on the test result). If a stimulus is not seen on the first presentation, the same point is repeated two more times. The point will be designated as normal if the stimulus is seen in one of these repetitions. A point is designated as abnormal (represented by "■") if a stimulus is not seen in any of the three presentations, as shown on Figure 3.7 [101]. Adopting this test strategy results in a short test duration, addressing one of the main requirements of ophthalmic professionals operating in time constraints during outreach field missions.

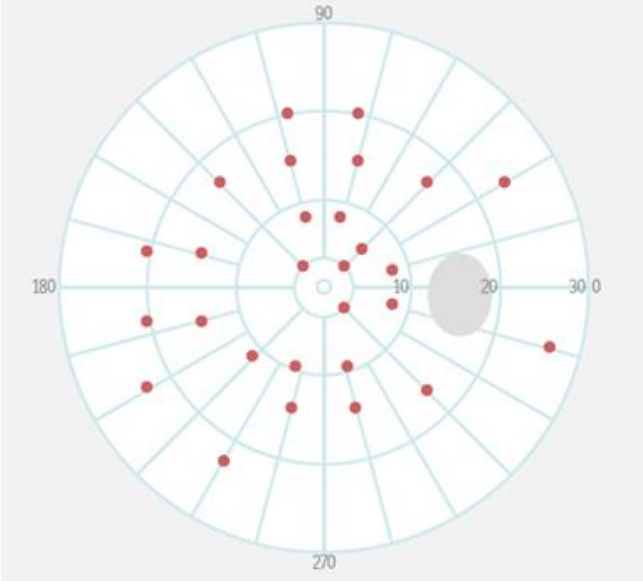


Figure 3.2 The 28 locations of Glaucoma Screening Test (GST) in Octopus (right eye)[101].

3.3 Smartphone Display Calibration

As previously mentioned, one of the major requirements for a visual field test platform is control over luminance of the background and stimuli. To achieve this on a smartphone, the intensity of light emitted by the display per unit area, also known as luminance, needs to be well known. The smartphone display needs to be calibrated to determine the mapping of pixel RGB (Red Green

Blue) values to luminance output, which is referred to as the gamma function [104], [105]. For this purpose, the Moto G5 display was calibrated with a luminance camera at the Light and Lighting Laboratory of KU Leuven located in the Technology Campus Ghent. Luminance measurements were taken at 8 distinct RGB intervals, ranging from 0 to 255, with the backlight set to its maximum brightness. The gamma function was derived from the luminance measurements according to Aslam et al. [104]. The minimum luminance of the display is 0.3 cd/m^2 and the maximum luminance is 475 cd/m^2 (see Figure 3.3).

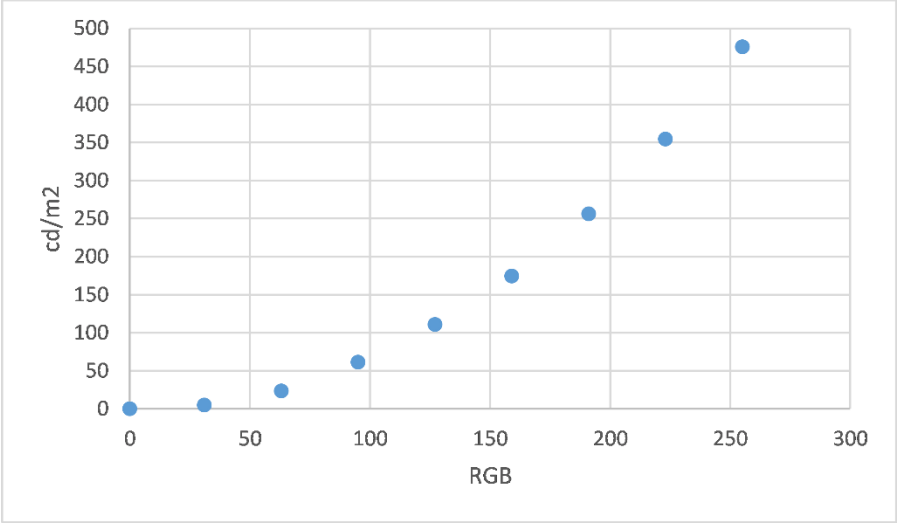


Figure 3.3 RGB to Luminance mapping of Moto G5 smartphone display. Luminance measurements for 8 different RGB values are plotted. The vertical axis represents luminance output with cd/m^2 and the horizontal axis represents pixel RGB values.

Sensitivity, which refers to the dimmest light stimulus that can be detected, is expressed with decibels (dB) in standard perimetry and has an inverse relationship with stimulus luminance [106]. Decibel values of the smartphone display were computed using the formula $dB = 10 * \log(L_{max}/L)$ where L_{max} is the maximum luminance of the display, and L is the stimulus luminance presented on top of the background [107]. The smartphone display can produce stimuli with intensities ranging from 0 dB to 30 dB, with a constant background set at 10 cd/m2, which is the background luminance used by the Humphrey SAP perimeter [108].

3.4 Test Parameters

Standard perimetry equipment like Humphrey (Humphrey Zeiss Systems) incorporate a number of key test parameters including stimulus duration, stimulus size, and reliability indices. With the Humphrey perimeter, stimuli are flashed for a duration of 200 ms. Normal patient responses are expected to start around 150 ms from the end of the stimulus taking average reaction times into consideration. Responses sooner than this are considered to be invalid which could be from random responses without detecting a stimulus. Stimulus size is also another key test parameter on standard perimetry equipment. There are five standard Goldmann sizes from size I through V but most testing is done with size III (0.43° diameter and 4.0 mm2 area) [109].

Test parameters for GES were set following the standard values of the Humphrey perimeter. Stimulus duration is set at 200 ms with a variable inter-stimulus gap in the range of 1800 ms to 2300 ms. There is a response window which starts 150 ms after the end of each stimulus with a response deadline of 1500 ms. Responses before and after the response window are considered invalid. Stimulus size is set at Goldman size III, which is commonly used as the default size on SAP equipment [108]. Stimulus size is adjusted by varying the number of pixels based on the distance from the fixation, to maintain a uniform angular size as the smartphone screen is a flat surface, unlike perimetry equipment which use a bowl surface.

Another key technical requirement for a visual field test platform is related to reliability indices to allow ophthalmic professionals assess reliability of the test. Since perimetric testing is subjective, unreliable visual field results are common, and identifying them is essential in clinical practice [110]. One of the major causes of unreliable test results is fixation loss. A patient's gaze is expected to stay stable at the fixation point throughout the test. Some patients fail to do so, resulting in an unreliable result. The other major cause of unreliable test results next to fixation losses, are false positive responses. Overly sensitive or so called trigger-happy patients might press the response button even when no stimulus has actually been seen [111], [112].

There are two reliability indices incorporated into GES to assist in the evaluation of test reliability; fixation loss rate and false positive response rate.

Fixation Loss: GES incorporates higher intensity stimuli that are randomly presented six times in the blind spot region to control for fixation losses, according to the Heijl–Krakau method [113]. As the blind spot is an absolute

scotoma of total blindness, response to stimuli presented in these region is counted as fixation loss error.

False Positive: In order to identify such responses, there are a total of 6 false positive catch trials where there is no stimulus presented during a stimulus duration. No response is expected from a perfect responder during these catch trials [114].

Manufacturers of the most widely used visual field perimetry device, Humphrey, recommend a cut-off value of 20% for fixation losses and 15% for false positive responses [115]. We suggest to stick to similar cut-off values for GES as well.

3.5 Normative Database Development

A screening visual field test compares patients' visual performance with that of a normal population incorporated as a normative database. Since stimulus intensity levels and other test parameters may vary among equipment, there is a requirement to have a distinct normative database for each perimetry setting [101]. In order to determine the correct stimulus intensity levels for each of the 28 locations, based on the retinal sensitivity of a normal population, a normative database should first be built, with the same platform. Hence, a separate application with a threshold testing algorithm was developed to build a normative database.

The thresholding algorithm presents stimuli at increasing intensity steps of 2 dB, beginning from the dimmest level i.e. 30 dB up to threshold level that can be detected. The test scene presented is similar to the screening app with a central fixation target, as shown on Figure. 3.5. Participants indicated detecting a stimulus by pressing the response button. Threshold sensitivity for each location corresponds to the first (dimmest) stimulus detected at that specific location. Threshold sensitivities for all of the 28 locations were obtained using this algorithm from normal participants. A total of 33 participants (10 male , 23 female) were recruited for this purpose after going through a comprehensive ophthalmic examination to check for healthy vision. Participants age ranged from 22 to 58 years, with an average of 31.7 (SD 11) years. Four eyes out of the 66 were excluded due to missing more than one location out of the 28 locations in the Octopus GST. Raw dB values obtained from the threshold test were divided into different age groups with an interval of 5 years, i.e. 20-25, 26-30, etc. The 5^{th} percentile was computed for each of

the 28 locations in all age groups. For age ranges not included in the study, intensity values were extrapolated according to the method proposed by Paolo Brusini [116].

3.6 Development of GES app

GES was developed as an Android application using Java as programming language, and using Android Studio as IDE. It uses the SQLite database available on Android operating systems. There are 3 main screens (activities) in the app (see Figure 3.4).

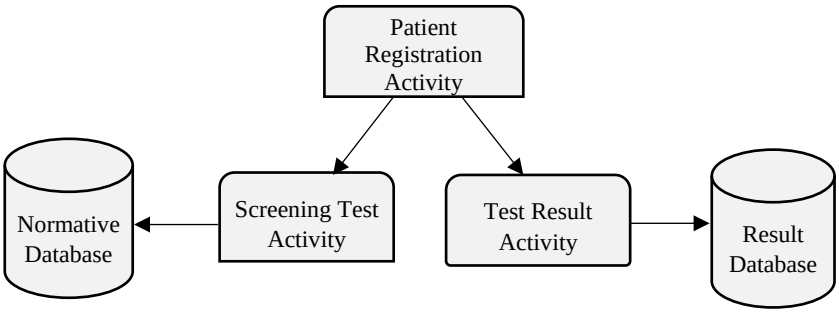


Figure 3.4 Architecture of GES app. Patient registration activity handles filling of patient details. Screening test activity handles the actual test for each eye using the reference normative database. Test result activity handles test results which are stored in the result database.

Patient Registration Activity (Main Activity)

The first activity that is presented when the app is launched is patient registration activity. Patient details, such as an identification number, name, age and gender are filled out on the first screen of the app (see Figure. 3.5). In order to detect visual field defects, stimuli are presented at various locations of the visual field, at an intensity level expected to be detected by a normal person of a similar age range.

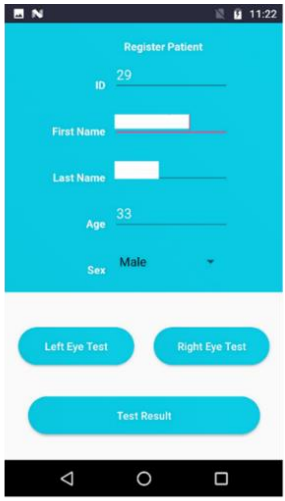


Figure. 3.5 First screen of GES app for patient registration

Test Scene

The test screen appears after selecting which eye (right or left) is to be tested. Upon selecting the test for one of the eyes, the app presents a test scene with a central fixation on the side of the selected eye, in landscape orientation.

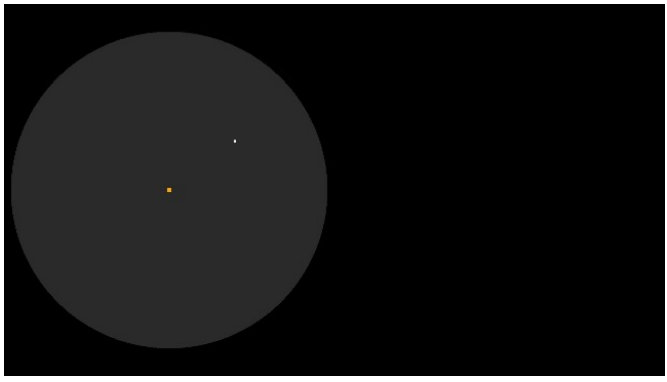


Figure 3.6 Test scene for left eye with a central fixation point and a sample stimulus presented at one of the locations.

Once the patient puts on the headset and is ready, the test will be started by pressing a button on the joystick. A double beeping sound confirms the successful start of the test. The app notifies the end of the test by playing a finishing sound. The headset has to be taken off to select the test for the other

eye, at the same time giving the patient a short rest before proceeding with the next test.

Test Result

Test results are presented on the screen separately for each eye. The visual field screening result is presented by plotting seen locations with "+" and missed locations with "■". Patient details and test parameters such as test duration and reliability indices (false positives and fixation errors) are presented in addition to the visual field result. A referral decision can be given by the health professional, by combining results from this screening test with other examinations including IOP (intra ocular pressure) or fundoscopy. The sample result shown in Figure 3.7, has a high fixation loss (poor fixation) since the patient detected 5 out of the 6 stimuli presented in the blind spot region. There are no false positive errors since the patient did not respond to any of the catch trials.



Figure 3.7 Sample screening result, with seen and unseen locations plotted on the left, and test parameters on the right.

3.7 Test Procedure

As previously mentioned, proper understanding of the test procedure by the patient is critical to obtain reliable test results. Therefore, the first step in performing the test is an explanation (training) by the ophthalmic professional. The patient needs to understand when to respond and which buttons to press on the joystick. To address this requirement, GES incorporates an animated

version of the test scene with small white dots appearing at various locations around the yellow central fixation target. Ophthalmic professionals use this feature to explain the nature of the test to patients. To make it easy for patients, all four coloured buttons on the right side of the joystick can be used for response. Once the patient is ready to go, the ophthalmic professional needs to fill in patient details, select the eye to be tested, mount the smartphone on the headset and let the patient wear the headset. The headset needs to be taken off to switch to the other eye allowing the patient to get some rest from the immersion experience, which might be stressful to some patients.



Figure 3.8 An ophthalmic nurse is seen explaining the test procedure to a patient on the left. The nurse is seen monitoring test progress while the patient performs the test on the right.

3.8 Conclusion

GES is designed based on technical and functional requirements any visual field test platform should fulfil, and based on the contextual requirements of eye care in developing countries. By calibrating the smartphone display, the requirement to guarantee accuracy of stimulus and background luminance was addressed. GES is able to maintain constant luminance of the background while manipulating stimulus intensities according to the gamma function

determined for the display. GES incorporated two major reliability indices to allow ophthalmic professionals asses test result reliability: the fixation loss rate and the false positive rate. These indices are presented next to the screening test result to help ophthalmic evaluate reliability of the result. Like any screening protocol available on SAP equipment, GES also incorporated a normative database of normal eyes to address the requirement to have a reference database.

GES adopted a screening strategy from Octopus perimeters, with a test duration of 1-1.5 minutes per eye. This strategy fits into the requirement of ophthalmic professionals who need to test several patients per day during outreach field missions. GES also incorporated a reference data of normal patients which was collected from 33 volunteers with normal vision. The mobile app was developed maintaining simplistic interactions with minimal screens taking into consideration the time constraint faced by ophthalmic professionals.

In summary, the current version of GES meets the basic requirements as a smartphone based low-cost and portable visual field screening tool. Results from a study of its acceptability and clinical validity are presented in the subsequent chapters. Future enhancements to the design and development of GES are possible including providing more screening strategies as options, expanding the normative database with more data from participants of all age ranges and machine learning features to predict glaucomatous test results.

Chapter 4

Acceptance of a Smartphone-based Visual Field Screening Platform for Glaucoma: Pre-Post Study

This chapter is a copy of the previously published article:

Nida EK, Bekele S, Geurts L, et al. Acceptance of a Smartphone-Based Visual Field Screening Platform for Glaucoma: Pre-Post Study. *JMIR Form Res* 2021; 5: e26602.

Abstract

Objective: To evaluate the acceptability of the Glaucoma Easy Screener (GES), a low-cost and portable visual field screening platform comprising of a smartphone, a stereoscopic VR headset and a gaming joystick.

Methods: A mixed-method study was conducted to evaluate the acceptability of GES, including 24 eye care professionals from four hospitals in Southwest Ethiopia. A pre-post design was employed to collect perspectives before and after using GES, using questionnaires and semi-structured interviews. A Wilcoxon signed ranks test was used to determine the significance of change in the scores of questionnaire items (two-tailed, CI=95%, alpha=.05). The questionnaire and interview questions were guided by the Unified Theory of Acceptance and Use of Technology (UTAUT).

Results: Positive results were obtained both pre-use and post-use, suggesting acceptance of mHealth solutions for glaucoma screening, using a low-cost headset through a smartphone and a game controller. There was a significant increase (CI=95%, alpha=.05) in the average score of 19 questionnaire items out of 22 (86%) post-use compared to pre-use. Ophthalmic professionals

perceived GES as easy-to-use, enabling the screening of glaucoma screening tests, especially during outreach to rural areas. However, positive evaluations are contingent on adequate accuracy of the tool. Moreover, ophthalmic professionals voiced the need to limit the tool to screening only, and not for diagnosis.

Conclusions: The study supports the feasibility of using a mobile device in combination with a low-cost VR headset and classic controller for glaucoma screening in rural areas. GES has the potential to reduce the burden of irreversible blindness due to glaucoma. Yet, a further assessment of its sensitivity and specificity is needed.

4.1 Introduction

Glaucoma is the leading cause of irreversible blindness worldwide, affecting about 64 million people [10], [11]. A large proportion of glaucoma cases worldwide are undiagnosed or sub-optimally managed [12]. More than half of the people living with the disease, in low-income countries, are unaware of the condition until it progresses to an advanced stage, resulting in visual impairment [15], [16]. As blindness due to glaucoma is irreversible, early detection of the disease is critical [65]. Visual field testing (VFT) is one of the major tests for screening and diagnosis of glaucoma [73]. The test assesses central and peripheral vision of each eye separately in order to detect vision loss, which, in case of glaucoma, gradually progresses from the periphery to the center. The test is mostly performed with SAP equipment which is expensive and not easily portable [117]. During the test, a patient is expected to look at the center of a dimly lit bowl-shaped area and press a response button upon seeing a small oval light appearing briefly at different places in the field of view [118]. The equipment records seen VFT unseen lights and provides a result at the end of the test, representing the visual field status of each eye. For people living in rural areas of low-income countries with limited access to ophthalmic care, glaucoma screening and diagnosis testing through VFT is near inexistent [16]. If an affordable alternative to the SAP equipment would become available, it is likely that more glaucoma cases could be detected, especially in rural areas where the burden of the disease is most significant [75].

Mobile health (mHealth), the use of mobile computing and communication technologies in health care and public health, is an emerging field. Its potential in improving health care delivery has been well demonstrated [50]–[52]. mHealth interventions have proven particularly successful in improving access to eye care in low-income countries challenged by a lack of eye-care professionals [119]. Recent efforts focused on designing affordable and portable technology for conducting VFT, using tablets [120] or smartphones with VR headsets [121]. Thus far, studies evaluating these VFT solutions are limited to clinical validation of prototypes in high-income countries, comparing their results against golden standard SAP equipment. SAP equipment comes at a cost of around 20,000 USD whereas the cost of a stereoscopic headset, smartphone and a gaming joystick currently comes at around 350 USD, hence only a fraction of the golden standard. Yet, such low-cost and portable alternatives are to be used in rural areas of low-income countries. The context of these areas is unique when it comes to technology adoption presenting challenges such as technological ineptitudes or

obstructive cultural beliefs [122], [123]. Successful adoption of new technology for healthcare in low-income countries is highly dependent not only on clinical accuracy but also on e.g., perceived ease-of-use and alignment with available infrastructure and protocols [124], [125]. Hence, complementary to verifying clinical accuracy of new technological innovations for health care, an assessment of the drivers for user acceptance is crucial.

We conducted a mixed-methods study to evaluate the acceptability of the Glaucoma Easy Screener (GES), a low-cost and portable visual field screening platform comprising of a smartphone, a stereoscopic headset and a gaming joystick (see Figure. 4.1).



Figure. 4.1 A person wearing the headset with a smartphone mounted at the front side and holding the joystick during a screening test.

The study included 24 eye care professionals from four hospitals in Southwest Ethiopia. A pre-post design was employed to collect their perspectives before

and after using GES, using questionnaires and semi-structured interviews. The questionnaire and interview questions were guided by the Unified Theory of Acceptance and Use of Technology (UTAUT) [126] which is widely applied to study adoption of technology. Previous studies have demonstrated the model's applicability for the adoption of mHealth and eHealth (electronic health) in low-income countries [122], [127], [128]. The specific research aims of this study were: (1) to assess the acceptability of GES, (2) to identify potential challenges that might affect the adoption of GES. Findings from this study suggest acceptance of GES for glaucoma screening, even in rural areas of low-income countries where patients lack technological aptitude. Nevertheless, our findings also highlight the importance of using the tool for screening only, not for diagnosis, and the importance of achieving adequate accuracy.

4.1.1 Related work

mHealth Adoption in Low-income Countries

A number of studies exist on the use and acceptance of mobile health in the context of low-income countries. mHealth solutions have been proposed for several health care interventions, such as support for HIV patients [129] neonatal child care [130], and diagnosis and treatment of pneumonia [131]. While most of these studies show positive results on the acceptability and usability of mHealth in low-resource settings such as sub-Saharan Africa, their findings cannot be generalized for eye care.

To the best of the authors' knowledge, there are only two studies on the acceptability and usability of mHealth for eye care in middle or low-income countries. Lodhia et al. [130] investigated the acceptability and usability of the Portable Eye Examination Kit (PEEK), a smartphone-based comprehensive ophthalmic examination system with clip-on hardware to examine for eye diseases like cataract which was deployed in Kenya. Based on qualitative analysis of interviews with patients, health care providers and key decision makers in ophthalmic care, the study found that through PEEK patients were able to overcome the barriers to accessing ophthalmic services. The acceptability of the solution to the health care professionals was further demonstrated by their perceived ability to use the solution easily. There were however deployment challenges identified by the study such as the need for governmental support, further training for health care professionals, ensuring data protection and access to smartphones at low-cost. Ludwig et al. [131] evaluated the feasibility of a smartphone-based ophthalmic imaging system (eyeGo) in India. The study found out that ophthalmic professionals were able

to quickly learn how to use the system. Patients also found it to be comfortable during the imaging process. The above two studies show encouraging results on the feasibility and potential acceptability of mHealth based solutions for eye care in low-income countries. However, both studies addressed the application of smartphones for ophthalmic imaging to examine diseases like cataract. More evidence is required on the acceptability and usability of mHealth to perform visual field screening test, which plays a key role in the screening and diagnosis of other eye diseases like glaucoma.

4.1.2 Unified Theory of Acceptance and Use of Technology (UTAUT)

The Unified Theory of Acceptance and Use of Technology (UTAUT) is widely applied to study adoption of technology [126], also in a health context [132]–[138]. The UTAUT model identifies in particular four drivers for technology adoption. ***Performance expectancy (PE)*** is the degree to which a user or potential user of an Information System believes that the system will contribute to the attainment of some benefits related to his/her job performance. ***Effort expectancy (EE*)** is the degree to which an Information system is easy to use. ***Social influence (SI)*** refers to the degree to which individuals perceive that influential people believe they should use a new information system. ***Facilitating conditions (FC)*** is defined as the extent to which an individual believes that there is technical and organizational infrastructure to support the use an information system. These four drivers are direct determinants of behavioral intention (BI) and ultimately use behavior (see Figure 4.2). Additionally, gender, age, experience and voluntariness of use are posited to moderate the four constructs.

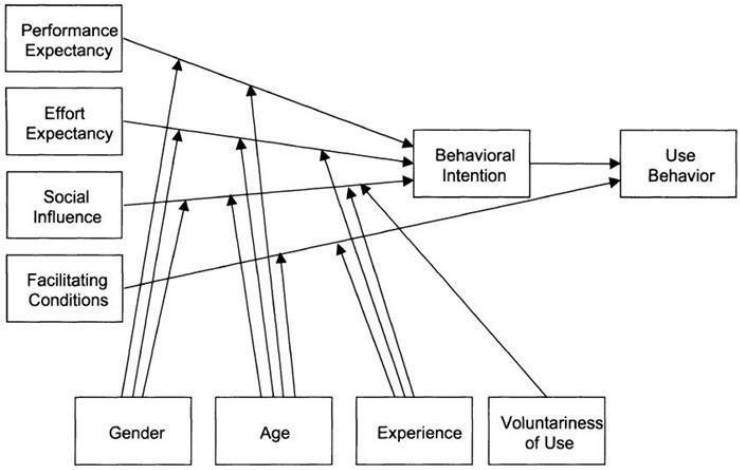


Figure 4.2. The UTAUT model by Venkatesh et al. [126]

Gender, age, experience and voluntariness of use are posited to moderate the four constructs.

Several studies have applied this model to scrutinize the adoption of mHealth and eHealth in various contexts, including low-income countries [122], [127], [128], [139]. Most of these studies adapt and extend the UTAUT model by tailoring items or adding items from the orginal study [126] to cater to that specific technology category or application domain [140], [141].

To the best of our knowledge, no studies have investigated acceptance of mHealth among eye healthcare professionals in the context of glaucoma screening. Given the unique context of designing mHealth solutions for glaucoma related eye care in low-income countries, further evidence is required from different countries to guide the design of mHealth for eye care in various contexts.

4.2 Methods

In this study the acceptance of a smartphone-based visual field-testing platform for glaucoma screening was evaluated through a combination of a UTAUT based questionnaire and semi-structured interviews. A pre-post design was applied to assess changes in attitude towards GES after practical use. We assessed the initial attitude towards the glaucoma screener with 24 ophthalmic professionals (OPs) who had never used an mHealth glaucoma screener before. Furthermore, we assessed changes in attitude after a first use of the screener. Qualitative analysis of interviews was used to further elaborate the quantitative data and gain additional feedback. This study was approved

by the ethical review board of the Institute of Health, Jimma University. A written informed consent was obtained from all participants.

4.2.1 Glaucoma Easy Screener

As VFT is a subjective test performed by the patient, and a clear understanding of the test procedures is required to obtain reliable results. Patients are supposed to stay focused and respond to stimuli presented which mainly relies on the performance of the patient. The role of the ophthalmic professional is to monitor test progress and guide the patient throughout the test. Patients performing the VFT for the first time are given explanations about the test, mostly focusing on the need for fixation of the eye and providing responses only after perceiving a stimuli. GES includes a demo animation to help OPs explain the test procedure for patients. The demo animates the actual test environment with stimuli flashing at different locations of the screen around a central fixation target. During the test patients wear the VR headset and respond to perceived stimuli using a joystick (see Figure 4.3).



Figure 4.3. Left: An ophthalmic nurse demonstrating the test procedure to a patient using the demo app. Right: The ophthalmic nurse is monitoring the progress of the test with GES.

Each eye is tested separately. A sound marks the end of test for each eye, upon which the OP is required to take off the headset and start the test for the other eye. The test duration per eye ranges from 2 minutes for those with no visual field defect, up to 5 minutes for those with an advanced visual field defect. At the end of the full test, OPs check the test results for each eye. The screening result is presented on the

smartphone screen by plotting seen and missed stimuli along with other test parameters, such as test duration and reliability indicators (see Figure 4.4

Figure 4.4).

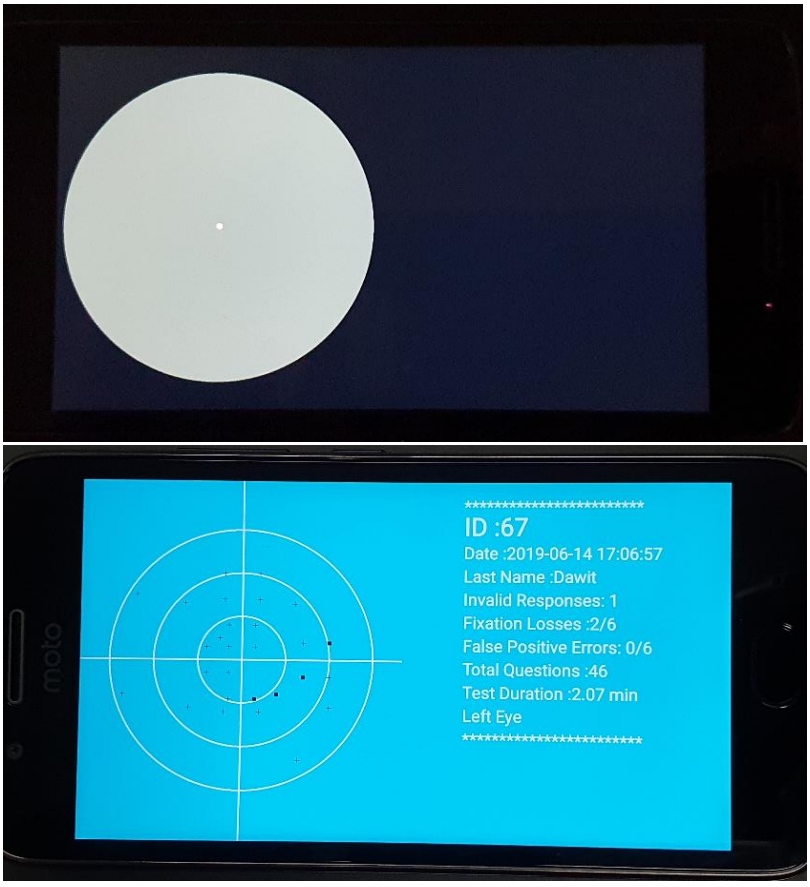


Figure 4.4. Test scene for left eye is shown at the top with a central fixation target and a sample result from GES test is shown on the bottom. On the test result plus (+) signs represent seen (normal) locations and black squares (■) represent missed (abnormal) locations.

4.2.2 Participants and Setting

The study was conducted at four different hospitals in Southwest Ethiopia in August and September 2018. The first hospital is Jimma University Medical Center in the town of Jimma, which is the only tertiary hospital for the Southwest region. Jimma University Medical Center has an ophthalmology department providing tertiary eye care for a population of more than 20

million in the region. About 23 OPs who are usually involved in the screening and diagnosis of patients, including ophthalmic residents, ophthalmic nurses, optometrists, cataract surgeons and opticians, were invited to participate in the study. Out of the 23, 19 accepted the invitation. Each OP was asked to recruit a patient for the user test among those he/she was screening on that day. There were no specific inclusion criteria for the selection of patients, but preference was given to older patients from rural areas as they are expected to be the most challenging to supervise during VFT due to limited familiarity with technology. The study also covered 3 other primary hospitals in the region namely: Saja Primary Hospital , Seka Chokorsa Primary Hospital and Agaro Primary Hospital. Unlike Jimma University Medical Center, these primary hospitals do not have well established eye units. They are also understaffed due to shortage of ophthalmic professionals. All OPs working in these three primary hospitals accepted the invitation to participate in the study. There are only two ophthalmic nurses at Agaro Primary Hospital and only one ophthalmic nurse at Saja Primary Hospital. Seka Chokorsa Primary Hospital relies on two IECW (Integrated Eye Care Workers) nurses with short ophthalmic training. They provide treatment for minor eye problems such as trachoma on top of their regular duties. A similar procedure to that of Jimma University Medical Center was followed with these participants at the three primary hospitals.

A total of 24 OPs completed both the pre-use and post-use questionnaire and participated in the interviews (see Table 4.1). Three additional OPs filled the pre-use questionnaire but were not available to use GES and hence were excluded from the study.

Table 4.1. Participants' profile

	Frequency
Gender	
Male	22
Female	2
Total	24
Age	
20-30	17
31-40	6
61-70	1
Total	24

Profession	
Ophthalmology Resident	11
Optometrist	6
Ophthalmic Nurse	4
IECW nurse	2
Cataract Surgeon	1
Total	24

4.2.3 Procedure and Instrument

Participants completed a pre-use questionnaire, before actual use of GES. The aim of the pre-use questionnaires was to evaluate OPs initial attitudes towards using a smartphone application for visual field testing, irrespective of the specific design and usage experience with the prototype. The pre-use questionnaire included items adapted to measure UTAUT constructs in the context of glaucoma. The UTAUT items were taken from Venkatesh et al. [126] but adapted to reflect the use of GES in the Ethiopian eye health care context (see Table 4.2).

Performance expectancy items assessed perspectives of ophthalmic professionals (OPs) regarding GES's ability to perform a reliable glaucoma screening. *Effort expectancy* items assessed how easily can OPs learn how to use GES, how easily can they administer the test with patients and their expectations regarding patients performing the test with minimal explanation. *Social influence* items assessed OPs expectations regarding how other senior staff members and patients will perceive them because of using GES. *Facilitating conditions* items assessed OPs perspectives regarding suitability GES with the current infrastructure, environmental conditions and availability of resources required for the successful utilization of GES in their workplace.

We also included items to assess OPs overall behavioral intention to use GES. We added these items in order to cross check for consistency of OPs responses for the four constructs and their ultimate intention to adopt GES in their daily practice. A positive score for the four constructs and a negative response for behavioral intention or vice versa might flag that additional factors need to be measured to explain acceptance of the technology.

All UTAUT items captured responses via a 5-point Likert scale with responses ranging from "strongly disagree" (1) to "strongly agree" (5) (see Appendix A). Upon completion of the pre-use questionnaire OPs could proceed to the next step of using GES. At the beginning of the VF test with GES, a brief demonstration (ca. five minutes) was given to each OP on how to use GES.

Support was given only for a total of three cases due to exceptional situations, upon request. At the end of the VF test with GES, OPs completed a post-test questionnaire, followed by an interview to follow-up on attitudes (see Appendix A).

The post-test questionnaire UTAUT items were slightly rephrased to reflect experience after use. Three extra items were included in the post-questionnaire relating to actual experience of using GES such as ease of administering the test with a patient, adequacy of the test result for making referral decisions and whether GES could be used in the current setting (see Table 2, items EE7, PE5 and FC5).

4.2.4 Data Analysis

Quantitative Data

Out of 22 items in the pre-use questionnaire, there were 6 items with 1 missing response out of the 24 participants (4%), 4items with 2 missing responses out of the 24 participants (8%) and one item with 3 missing responses out of the 24 participants (12%). Out of 25 items in the post-use questionnaire, there were two items with 1 missing response out of the 24 participants (4%) and 3 items with 2 missing responses out of the 24 participants (8%). All missing responses were replaced using the median imputation method [142]. Next, data was checked for normality, skewness and kurtosis [142]. Only one item (EE2) in the post-use questionnaire, had a kurtosis issue with absolute value of the kurtosis being slighlty greater than three times the standard error. Next, internal consistency of the constructs were through Chronbach's alpha. Unfortunately, for several constructs, these did not show a sufficient internal reliability (<0.7) [143]. Therefore, the decision was made to report results at the item-level rather than the construct level.

To assess whether attitudes changed significantly after use, a Wilcoxon signed ranks test was used to determine the significance of change in the scores (two-tailed, CI=95%, alpha=.05), before and after usage of GES. As this study is exploratory in nature, there is no correction for a familywise error inflation. Instead, we provide confidence intervals, that allow readers to get a direct understanding of size and effect. SPSS and Microsoft excel were used for the data analysis and Seaborn Python data visualization library [144] was used to illustrate data distribution with violin plots.

Qualitative Data

Qualitative data were obtained through interviews. Initial interview questions were prepared pertaining to the four UTAUT constructs. Additional questions were included for every respondent based on our observations during the screening test. Respondents were also invited to provide general feedback on GES at the end of the interview. The interviews were conducted immediately after use of the GES, to ensure respondents had a fresh memory of the usage experience. All interviews were audio recorded and transcribed verbatim. Interview data were categorized, ccording to the major UTAUT constructs. Additional comments from OPs that did not fit to any of the categories were handled separately, as a comprehensive feedback on GES.

4.3 Results

Here we present the quantitative results for each of the five categories, along with the qualitative findings.

Table 4.2. Mean scale scores pre-use and post-use.

Scale	Mean (SD) Pre-use	Mean (SD) Post-use	95% CI	*P* value[a]
Performance Expectancy				
PE1 This platform will be useful during outreach screening.	4.04 (0.81)	4.63 (0.49)	+0.58 (0.21-0.96)	0.006
PE2 The platform will enable me to make more accurate diagnosis.	3.42 (0.72)	3.88 (0.95)	+0.46 (0.15-0.76)	0.008
[c]PE3 I do not expect that this platform can be used for a reliable eye exam.	3.29 (0.95)	3.33 (0.96)	+0.04 (-0.54-0.62)	0.893
PE4 More glaucoma cases can be detected by the platform.	3.38 (0.71)	4.17 (0.96)	+0.79 (0.34-1.24)	0.005
[b]PE5 The results presented are informative enough to make referral decisions	-	4.21 (0.72)	-	-
Effort Expectancy				
EE1 I think the platform will be easy for me to administer visual field tests.	3.88 (0.61)	4.79 (0.41)	+0.92 (0.59-1.24)	0.000
EE2 I think learning how to use the platform will be easy	4.00 (0.72)	4.71 (0.46)	+0.71 (0.44-0.97)	0.000
EE3 It will be easy to have patients wear the VR headset	3.63 (0.92)	4.42 (0.88)	+0.79 (0.42-1.16)	0.001
EE4 Compared to the FDT, administering	3.33 (0.82)	4.29 (0.85)	+0.96 (0.46-1.46)	0.002

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Scale	Mean (SD) Pre-use	Mean (SD) Post-use	95% CI	*P* value[a]
visual field testing with this platform will be easier				
EE5 The platform will be easier for patients from rural areas compared to the FDT		4.25 (1.19)	+0.58 (-0.01-1.18)	0.047
EE6 Patients can easily use a joystick for response.	3.71 (0.95)	4.25 (0.74)	+0.54 (0.15-0.94)	0.012
[b]EE7 My interaction with the platform was clear and understandable.		4.42 (0.58)	-	-
Social Influence				
SI1 I think the senior ophthalmologist staff will recommend the platform for glaucoma screening.	3.67 (0.87)	4.08 (0.93)	+0.42 (-0.10-0.93)	0.083
SI2 In general, I think the platform will be seen as useful by the ophthalmology department.	3.83 (0.76)	4.63 (0.49)	+0.79 (0.46-1.12)	0.001
SI3 My colleagues will support my use of this platform	3.67 (0.96)	4.46 (0.66)	+0.79 (0.38-1.20)	0.002
SI4 My patients will be open to the use of this platform	3.46 (0.98)	4.50 (0.59)	+1.04 (0.58-1.50)	0.001
SI5 If I use the platform, I will be considered as an advocate of technology by my colleagues.	4.04 (0.86)	4.17 (0.92)	+0.13 (-0.23-0.48)	0.477
Facilitating Conditions				
FC1 All the necessary resources to use the platform will be easily available.	3.33 (1.13)	4.00 (1.02)	+0.67 (0.22-1.11)	0.007
FC2 The platform will not be expensive for our clinic to purchase.	3.75 (1.03)	4.21 (0.83)	+0.46 (0.01-0.91)	0.046
FC3 The platform can be used with our existing infrastructure	3.88 (0.95)	4.13 (0.85)	+0.25 (-0.24-0.74)	0.211
FC4 Charging the smartphone will not be a challenge, even during outreach missions.	3.75 (0.99)	4.29 (0.75)	+0.54 (0.11-0.97)	0.018
[bc]FC5 The platform cannot be used in the current setting.	-	3.63 (1.21)	-	-
Behavioral Intention				
BI1 If made readily available, I intend to use the platform in the near future.	4.08 (0.50)	4.67 (0.48)	+0.58 (0.34-0.83)	0.000

Scale	Mean (SD) Pre-use	Mean (SD) Post-use	95% CI	*P* value[a]
BI2 When available, I would like to take the platform along with other kits for outreach mission.	3.96 (0.62)	4.50 (0.59)	+0.54 (0.21-0.87)	0.005
BI3 I am looking forward to using this platform when it is available.	4.00 (0.42)	4.67 (0.48)	+0.67 (0.46-0.87)	0.000

[a] Wilcoxon signed ranks test (non-parametric).

[b] Extra item included only in the post-use questionnaire.

[c] Inverted Items

4.3.1 Performance Expectancy (PE)

All pre-use PE items scored above 3 (neutral), with PE1 (*This platform will be useful during outreach screening)* scoring the highest with a mean of 4.04 (SD 0.81), and PE3* (*I do not expect that this platform can be used for a reliable eye exam*) scoring the lowest, with a mean of 3.29 (SD 0.95) (see Figure 4.5 pre-use). Post-use, all PE items scored above 3, again PE1 scoring highest value with a mean of 4.63 (SD 0.49), and PE3 the lowest, with a mean of 3.33 (SD 0.96) (see Figure 4.5 post-use). Moreover, all PE items increased their score in the post-use, of which items PE1, PE2, reached significance, while PE3 and PE4 did not reach significance (see Table 4.2).

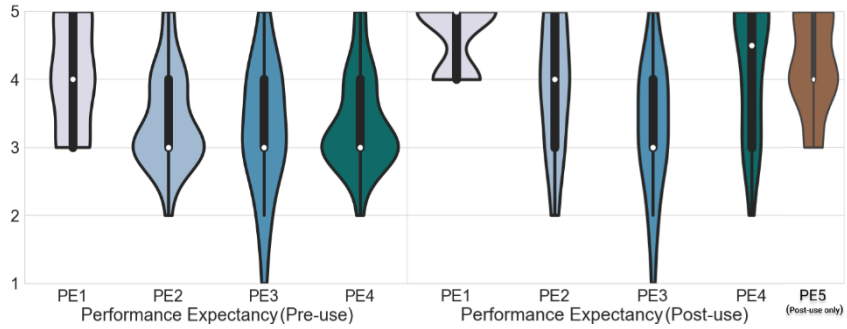


Figure 4.5. Performance expectancy scores of pre-use on the left and post-use on the right. The white dot represents the median value, the black bar represents the interquartile range and the thin black bar denotes the 95% confidence interval.

From the interviews we learned that while OPs supported the portability of GES for screening during field campaigns, such as the outreach mission, they also expressed their concern on its accuracy.

P15 (ophthalmic resident): I think it will be useful because you can't carry the FDT (Frequency Doubling Technology) to the outreach mission but this one is easily portable. You can refer patients you suspect during screening. But I have no idea about its sensitivity and specificity.

P7 (optometrist): If the result is valid about its sensitivity and specificity, I think it is informative enough. But it would be good if it includes something like a percentage of the defect which will allow us to have a kind of cut point where we can say it is fine. If it is below that and more critical if it is above that level. Another important issue is… in rural areas you may not have the other tools like an ophthalmoscope to examine the optic nerve. So, any macular disease or scar could cause visual field defect. So, you can't immediately conclude that the defect is due to glaucoma.

4.3.2 Effort Expectancy (EE)

All pre-use EE items scored above 3 (neutral), with EE2 *(I think learning how to use the platform will be easy)* scoring the highest with a mean of 4.00 (SD 0.72), and EE3 (*It will be easy to have patients wear the VR headset*) the lowest, with a mean of 3.63 (SD 0.92) (see Figure 4.6 pre-use). Post-use, all EE items scored again above 3, with EE1 (*I think the platform will be easy for me to administer visual field tests*) scoring highest value with a mean of 4.79 (SD 0.41), and EE5 the lowest (*The platform will be easier for patients from rural areas compared to the FDT*), with a mean of 4.25 (SD 1.19) (see Figure 4.6 post-use). Moreover, all EE items increased their score in the post-use and reached significance (see Table 4.2).

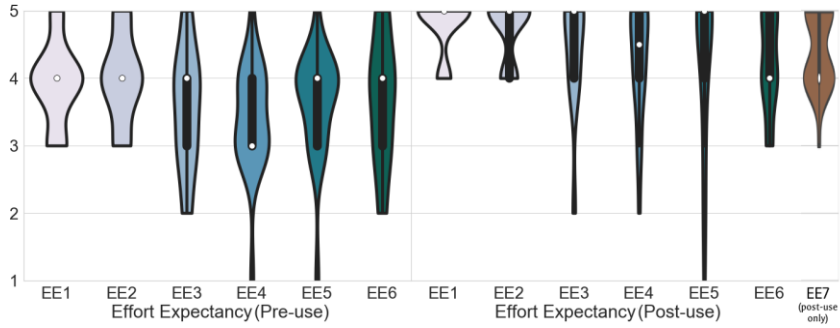


Figure 4.6. Effort expectancy scores of pre-use on the left and post-use on the right. The white dot represents the median value, the black bar represents the interquartile range and the thin black bar denotes the 95% confidence interval.

There were no specific difficulties expressed during the interviews related to administering the test with patients.

P6 (ophthalmic resident): This is easy for the patient. The joystick is good for the patient because it is possible to press any of the buttons. It won't be a problem even if the patient presses another button by mistake. In addition, its cost very little […] For instance, you can't carry the FDT to rural areas but this one is portable.

P1 (ophthalmic resident): For me, it is almost similar. Your tool has a central target, the FDT also has a similar target. So, I don't see much difference. But in terms of professional effort I think this platform may be simpler [than the FDT] when we get used to it in the future.

P17 (ophthalmic resident): What surprises me is when I read books they mention the FDT as a portable perimeter compared to Humphrey. But this is really portable.

4.3.3 Social Influence (SI)

All pre-use SI items scored above 3 (neutral), with SI5 (If I use the platform, I will be considered as an advocate of technology by my colleagues) scoring highest with a mean of 4.04 (SD 0.86) and SI4 (My patients will be open to the use of this platform) the lowest, with a mean of 3.46 (SD 0.98) (see Figure 4.7 pre-use). Post-use, all SI items scored above 3, SI2 (In general, I think the platform will be seen as useful by the ophthalmology department) scoring the highest value with a mean of 4.63 (SD 0.49), and SI1 (I think the senior ophthalmologist staff will recommend the platform for glaucoma screening) the lowest, with a mean of 4.08 (SD 0.93) (see Figure 4.7 post-use). Moreover, all SI items increased their score in the post-use. All items reached significance except SI1 and SI5 which did not reach significance (see Table 4.2).

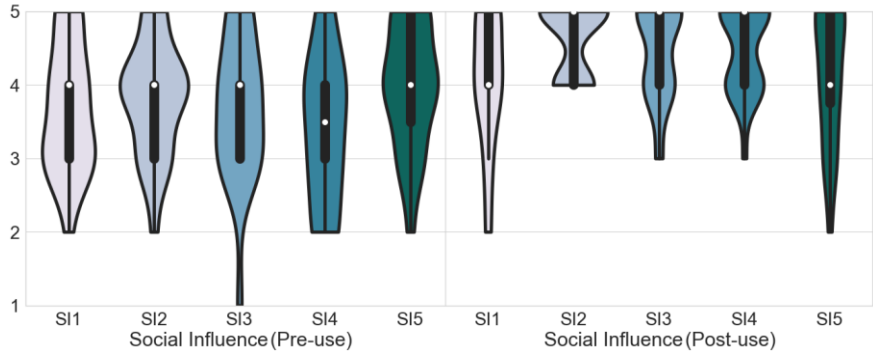


Figure 4.7. Social Influence scores of pre-use on the left and post-use on the right. The white dot represents the median value, the black bar represents the interquartile range, the thin black bar denotes the 95% confidence interval.

All OPs were confident about GES acceptance by colleagues and patients. Some OPs were doubtful about support from hospital management.

> *P21 (optometrist): We don't have any worry about that [patients' acceptance]. They will even feel like being diagnosed/examined more in detail. For instance, patients feel more treated when we examine them with slit lamp instead of torch light, even though the finding could be the same.*

> *P2 (ophthalmic nurse): I am not sure about the hospital management, but our department will for sure support it.*

4.3.4 Facilitating Conditions (FC)

All pre-use FC items scored above 3 (neutral), with FC3 (The platform can be used with our existing infrastructure) scoring highest with a mean of 3.88 (SD 0.95), and FC1 (All the necessary resources to use the platform will be easily available) the lowest, with a mean of 3.33 (SD 1.13) (see Figure 4.8 pre-use). Post-use, all FC items scored above 3, FC1 scoring highest value with a mean of 4.29 (SD 0.75), and FC1 the lowest, with a mean of 4.00 (SD 1.02) (see Figure 4.8 post-use). Moreover, all FC items increased their score in the post-use. All items reached significance except FC3 which did not reach significance (see Table 4.2).

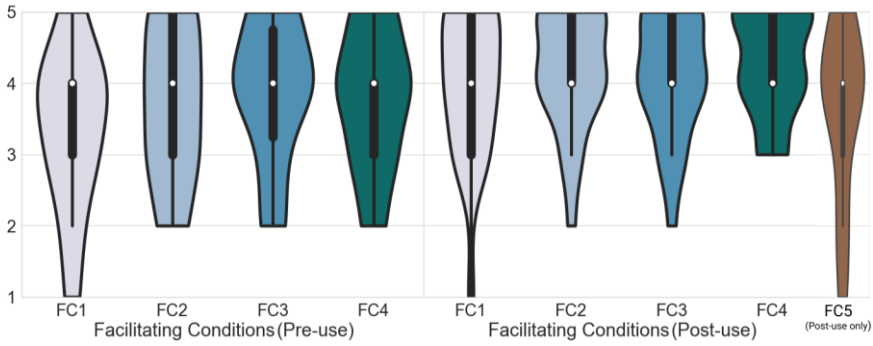


Figure 4.8. Facilitating condition scores of pre-use on the left and post-use on the right. The white dot represents the median value, the black bar represents the interquartile range and the thin black bar denotes the 95% confidence interval.

There were no major concerns raised during the interviews relating to this category with OPs showing optimism on its affordability and possibility of charging the smartphone even in the worst conditions of having no access to electricity by using solar chargers.

> *P8 (ophthalmic resident): I don't think there will be a challenge with the battery. The worst case we can use solar chargers which are very common nowadays.*

> *P13 (cataract surgeon): I think this can be even affordable by the ophthalmologists to buy one for their own let alone the institutions. They can also use it in their private clinic.*

4.3.5 Behavioral Intention (BI)

All pre-use BI items scored above 3 (neutral), with BI1 scoring highest with a mean of 4.08 (SD 0.50), and BI2 the lowest, with a mean of 3.96 (SD 0.62) (see Figure 4.9 pre-use). Post-use, all BI items scored above 3, BI1 and BI3 scoring highest value with a mean of 4.67 (SD 0.48), and BI2 the lowest, with a mean of 4.5 (SD 0.59) (see Figure 4.9 post-use). Moreover, all BI items increased their score in the post-use. All items reached significance (see Table 4.2).

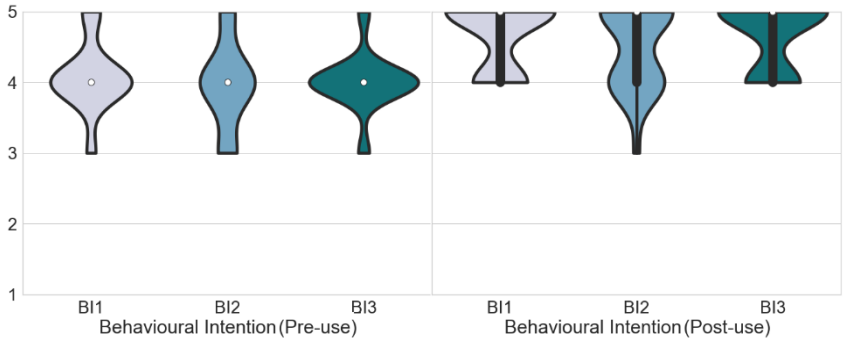


Figure 4.9. Behavioural Intention scores of pre-use on the left and post-use on the right. The white dot represents the median value, the black bar represents the interquartile range and the thin black bar denotes the 95% confidence interval.

Many OPs expressed their intention to use the system in the future, mentioning the dire need for a portable visual field screening tool.

> *P19 (ophthalmic resident): I think we will use it as it is easy and very quick. The major reason we don't use FDT for many of the patients is because of the duration we spend on a patient. If patients can easily understand it, we will for sure use it.*

> *P2 (ophthalmic nurse): I am ready to use it because glaucoma is a challenge especially during outreach missions. We refer patients by examining them only with an ophthalmoscope.*

4.3.6 Summary of Qualitative Findings

Feasibility of low-cost VR and game controllers

During this study, there were no significant difficulties found in learning how to use GES. OPs were able to administer the test with a patient, following a brief demonstration. Though for most patients, it was their first experience to wear a VR headset and use a joystick, all of them were able to understand the test procedure and performed the test successfully in a first attempt. We observed that even old patients from rural areas, with limited familiarity with technology, were able to perform the test with GES based on the explanation given by OPs.

Moreover, ophthalmic nurses, optometrists and IECW nurses at the primary hospitals saw an additional advantage in using GES, compared to the OPs at Jimma University Medical Center tertiary hospital. With almost no attention given to eye care at the primary level in Ethiopian health system [48], they usually suffer from lack of resources including testing equipment. They usually rely on simple and basic tests with torch lights and simple magnifying lenses. They believed that when tested with a kit like GES, patients will be more satisfied due to a '*feeling'* of being better assessed with an instrument.

> *P24 (IECW nurse): Patients are happier when examined with instruments. Even using the simple loop lens makes a lot of difference for patients. So, if we examine them with this tool, they might feel like they have been tested not only for glaucoma but for all kinds of eye problems.*

> *P21 (optometrist): They will even feel like being diagnosed/examined more in detail. For instance, patients feel more treated when we examine them with slit lamp instead of torch light even though the finding could be the same. Patients will consider this a more advanced instrument which will give them a psychological satisfaction of feeling well treated.*

Useful for screening, not diagnosis

In the current study, two IECW nurses at Seka Primary Hospital, who had limited ophthalmic training, had no difficulties in using GES. However, when it came to interpreting the results of the visual field screening test, they expressed reservations. They believe that the actual identification of glaucomatous visual field defects requires further training. A similar concern was also raised by ophthalmic residents at Jimma University Medical Center tertiary hospital during the post-use interviews. While they believed that GES could improve the capacity of nurses at primary level health centers in detecting glaucoma cases, they recommended its deployment to be accompanied by a training on how to interpret results in order to give referral decisions. They also indicated a risk of non-ophthalmic professionals misusing it as a diagnostic tool to prescribe glaucoma medication to patients. They insisted that GES' use should be limited to screening, not diagnosis, but also articulating it should fulfill the criteria for clinical accuracy.

> *P24&25 (IECW nurses): The procedure to use it was very simple for us to perform. But we don't have any clue as to how to make conclusions based on the results. We need additional knowledge for that.*

> *P8 (ophthalmic resident): A concern I have is regarding the knowledge gap regarding visual field in general hospitals and health centers. Health professionals (non-ophthalmic) need training before using this platform. They*

might misinterpret the results and use it as a shortcut to prescribe medications to the patient. Remember this is a screening tool, not a diagnosis tool. So, the tool might be abused.

Precising desired accuracy of the tool

In our sample, there were differences among OPs as to what level of accuracy is acceptable for a screening test. Only three OPs were expecting a VFT result similar to that of SAP and FDT equipment, while others considered a lesser accuracy (as currently obtained by GES [145] to be adequate and even more suited for a screening purpose).

P7 (optometrist): If the result is valid about its sensitivity and specificity, I think it is informative enough.

P19 (ophthalmic resident): The information on the result is enough as to me. Remember this will most probably be used by non-ophthalmic professionals. Adding other details may not add any value since they don't have any knowledge. I think the basic information are included.

P15 (ophthalmic resident): With the FDT we have get details like the standard deviation, pattern standard deviation and others which are important for glaucoma diagnosis. But for this one we don't know the details.

Integrating with patient records

Finally, a last topic discussed was the integration of the data given by GES in the current trail of patient data. There were also differences among OPs on how to integrate GES test results with the existing paper-based patient record management at the hospitals. Four OPs suggested the possibility of integration with a future digital health record system while others considered it to be sufficient to get the results on the smartphone screen, similar to their experience during this study. Overall, the interviews suggested this part of health care has yet to mature and that challenges in current infrastructure in low-income countries may still warrant a tangible output.

P4 (optometrist): There is a new technology coming to get rid of the paper documents and automate the patient record keeping. If that system is in place the app can easily be integrated with the system. But with the current setup there should be a paper print out to be enclosed in the patient's folder.

P3 (ophthalmic resident): Since it is a screening tool, not a diagnosis tool, as to me there is no need for a printout because I will still have the result on the mobile even if the patient folder is lost.

4.4 Discussion

Glaucoma, also referred to as the "silent thief of sight" [146], is a major cause of irreversible blindness worldwide [147], and particularly in Africa where it accounts for 15% of all blindness. Since glaucoma screening and diagnosis depend on expensive, stationary equipment, having a timely eye examination is almost impossible for people for living in rural areas of low-income countries like Ethiopia. This study assessed the acceptance of a low-cost and portable glaucoma screening solution through UTAUT based surveys, pre- and post-use, in four different hospitals in Southwest Ethiopia. Positive results were obtained pre-use, suggesting acceptance of mHealth solutions for glaucoma screening, using a low-cost headset through a smartphone and a game controller. Moreover, almost all scores improved significantly post-use, after using GES in particular. Ophthalmic professionals perceived GES as a handy and easy-to-use kit for their fight against glaucoma (Effort Expectancy). They believed GES would enhance the screening of glaucoma (Performance Expectancy), especially during outreach field missions to rural areas due to its portability and short test duration. They also considered GES to be usable within the existing health care system (Facilitating Conditions) and believed its use would be favored by their colleagues and management (Social Influence). The positive scores on the different drivers were reinforced by the high scores on their behavioural intention to use GES in their daily practice. Complementing the quantitative results, the observations and interviews confirmed the enthusiasm for using GES in the future.

Perceived ease of use (effort expectancy) has been identified to be one of the major factors influencing mHealth adoption by health professionals [48], [124], [125]. One of the major challenges Ethiopian OPs face while administering VFT is the extra effort required to explain the test procedure to patients from rural areas with little familiarity with technology, to the extent of not even having experience to use a TV remote control [48]. Both quantitative and qualitative results indicate that GES is easy to use even with patients from rural areas. This reinforces findings of Lodhia et al. [130] and Ludwig [131] that patients in rural areas are able to overcome the barriers to using technologies for ophthalmic services. Hence, this findings suggest that

cultural beliefs or lack of technological ineptitude, often mentioned as barriers for adoption [122], [123] will not hamper acceptance of GES. In sum, this supports the feasibility of using a mobile device in combination with a classic controller and low-cost VR headset.

Given the dire shortage of ophthalmic professionals in rural areas of low-income countries [16], mHealth solutions for eye care such as GES aim to allow for examinations to be performed by lesser trained or educated healthcare workers, e.g., non-ophthalmic nurses. The major concern of highly trained OPs at the tertiary hospital was that GES might be mis-used for diagnosis by less trained nurses at the primary level, in addition to screening. This finding contrasts with the study by Chang et al. [148] who identified concerns of confidentiality of data, and worry over job security. Our study suggests that concerns of ophthalmic professionals are mainly focused on inappropriate use of the tool, not job erosion. Hence, any mHealth solution for eye health care should carefully strike the balance between empowering primary care level workers who have lesser specialized training and enabling abuse, overstepping from screening to unwarranted diagnosis.

Similar to findings by Lodhia et al. [130], where health professionals expressed the need for determining clinical accuracy of Peek before use as a screening tool, in our study OPs recommended further research on sensitivity and specificity. This highlight that positive scores on the performance expectancy were given '*conditionally'*, under the assumption that clinical accuracy would be satisfactory.

4.4.1 Limitations and Future Work

Although this study provides interesting insights into the factors that influence OPs acceptance of a mobile health solution for eye care, this study comes with limitations. First, given the dire shortage of ophthalmic professionals in the Southwest region of Ethiopia, the sample was small. Second, OPs perceptions post use were measured after a single use of GES. Hence, we were not able to measure their perspectives based on long-term, continued usage. Therefore, possible additional challenges not identified by this study might still arise during a long term use. Lastly, as we adapted items from the original UTAUT questionnaires and added our own items, internal consistency at the construct level was no longer achieved (Chronbach's alpha <0.7 for 2 constructs in pre-use and 4 constructs in post-use). This necessitated that quantitative analysis

was performed for individual items, and may introduce overal a lesser robust measurement. Several studies support the analysis of individual items instead of constructs in these situations. For example, Aljarallah S and Lock R [149] report on users' perspective towards software sustainability and present much of their analysis at item level despite reporting low level of Cronbach's alpha (below 0.7) for some of the constructs and Marchewka JT and Kostiwa K [150] report much of their descriptive analysis from a UTAUT driven questionnaire at an item-level after presenting construct level reliability measures. Furthermore, Elo A-L et.al. [151] and Clason DL and Dormody TJ [152] demonstrated validity of analyzing individual survey items (not summated). By providing descriptive results for all items, we hope to have addressed this matter sufficiently.

4.5 Conclusion

This chapter presented a mixed-method study on the acceptance and use of a low-cost and portable smartphone-based visual field screening tool for glaucoma (GES), at four hospitals in Southwest Ethiopia. We combined survey data and interviews of 24 ophthalmic professionals. Both quantitative and qualitative results suggested high levels of acceptance. Additionally, this study provided better insight into the factors influencing health professionals acceptance of mHealth interventions for eye care in low-income countries like Ethiopia. We found that ophthalmic professionals perceived GES as easy-to-use, enabling the screening of glaucoma screening tests, especially during outreach to rural areas. Even older patients from rural areas, with limited familiarity with technology, were able to perform the test with GES, and valued a 'technical' assessment. Nevertheless, as frequently indicated by the OPs, a further assessment of its sensitivity and specificity is needed as positives evaluations are contingent on the assumption of adequate accuracy. Moreover, this tool is suited for screening, not diagnosis. Accounting for these caveats, GES has the potential to reduce the burden of irreversible blindness due to glaucoma.

Chapter 5

Accuracy of a smartphone based low-cost and portable visual field screening tool: pilot validation study

Parts of this chapter have been presented as a poster presentation on the 22nd Congress of the European Association for Vision and Eye Research (EVER) Conference in October 2019. The abstract was published on Acta Ophthalmologica, Volume 97, Issue S263 Special Issue: Abstracts from the 2019 European Association for Vision and Eye Research Conference

E. K. Nida, E. Vandewalle, K. V. Keer, V. V. Abeele, and L. Geurts, "Clinical validation trial of Glaucoma Easy Screener (GES) as a low-cost and portable visual field screening tool," Acta Ophthalmol. (Copenh.), vol. 97, no. S263, 2019, doi: 10.1111/j.1755-3768.2019.5226.

Abstract

Purpose: The aim of this study is to compare the performance of the Glaucoma Easy Screener (GES), as a low cost and portable visual field screening tool, to the glaucoma screening test (GST) from Octopus.

Methods: GES is comprised of a Moto G5 smartphone, the Homido v1 virtual reality headset and a gaming joystick for user input. The screening app's design is based on the recently introduced Octopus GST screening test. The

test contains 28 locations in the central 30^0. Test stimuli at each location are presented at an intensity level that can be detected in 95% of the time, in case of a normal visual field. The app monitors false positive errors with catch trials and fixation losses using the blind spot method. The test result is presented with a plot of seen and missed locations, along with other parameters, including test duration and reliability indices. To evaluate agreement between Octopus GST and GES, 36 eyes of 18 participants were tested both with GES and Octopus GST.

Results: There is a good level of agreement between Octopus GST and GES. Out of 36 eyes, there was 100% agreement for 17 eyes, 90-99% agreement for 11 eyes ,80-89% agreement for 4 eyes and 4 eyes had agreement below 80%, with lowest agreement value being 64%. Summed over all eyes, there was above 85% agreement for 24 locations. The remaining 4 locations had an agreement between 78%-85%. Test duration was slightly higher for GES, with an average of 2 minutes per eye compared to 1.1 minutes with Octopus GST.

Conclusions: Results from this clinical trial show a good level of agreement between GES and Octopus GST. This suggest that GES can serve as a low-cost and portable visual field screening kit, to complement other glaucoma tests, and to make referral decisions in situations where standard equipment is not available.

5.1 Introduction

Glaucoma is one of the leading causes of irreversible blindness worldwide [153]. More than 70% of glaucoma cases in low and middle income countries are undiagnosed, due to lack of ophthalmic professionals and diagnosis equipment [154], [155]. Because of the asymptomatic nature of the disease, inadequate eye care service and lack of awareness, many patients tend to visit hospitals after they have become either unilaterally or bilaterally blind [156]. Unlike cataract and trachoma, blindness due to glaucoma is irreversible [157], [158]. However, if detected early, blindness due to glaucoma can be prevented [159].

Assessment of the visual field with perimetry is a key test for the detection and management of glaucoma [160]. The test is mainly performed on standard automated perimetry (SAP) equipment which is expensive and less portable [161]. In sub-Saharan countries like Ethiopia, SAP equipment is not available at rural health facilities, as eye care is not well integrated into rural primary health care [162]. Likely, more glaucoma cases could be detected earlier if visual field test are made available and affordable, especially in rural areas where the burden of the disease is more significant [163].

Some portable perimetry alternatives exist which were developed using tablets, to make the visual field test more easily available outside hospital settings [161], [164]. These tablet-based tests require the patient to sit at a fixed distance from the tablet. The health professional is asked to monitor the patient throughout the test to make sure the distance is maintained. The test will be paused to readjust the distance if the patient makes movements that affect distance from the tablet [164]. Though these tablet-based alternatives are portable and less expensive compared to SAP equipment, the effort required to initially adjust the patient at a fixed distance and monitoring it throughout the test might not be easy. This challenge will be more pronounced in situations like ophthalmic outreach missions in rural areas of Ethiopia, where there is a large patient turnout each day [48]. Furthermore, it is not possible to control lighting conditions of the environments with tablet-based tests which might interfere with stimulus or background luminance.

In addition to tablets, recent developments are also coming up, with visual field tests using VR headsets with built in displays [165]–[167]. These alternatives with VR headsets, offer the advantage of maintaining a fixed distance from the eye throughout the test, and lighting conditions are also more

controlled compared to the tablets. Most of these devices have gone through clinical validation, which has shown good levels of correlation with the gold standard SAP equipment. However, VR devices with built-in displays are still relatively expensive which might still make them unaffordable in rural areas of low-income countries.

Smartphone VR, comprising an ordinary smartphone mounted on a low-cost VR headset, can be an even cheaper and more portable alternative for visual fields compared to those with built-in displays. VR headsets, that support multiple smartphone models, are now available for affordable prices. Though smartphone VR offers a significant price advantage, it is not widely explored for visual field tests. Portable Perimeter (PP) [168], which uses the Google Cardboard 2015 VR headset with a Nexus 6P smartphone, is the only initiative as far as our knowledge is concerned. The app is designed to perform a threshold visual field test with a staircase algorithm. Initial parameters are loaded from a server to the smartphone and results are sent back to the server at the end of the test. The researchers have reported a good level of agreement with the HFA perimeter. This app can be useful for home and bedside tests in developed countries with reliable internet access. However, remote areas of developing countries like Ethiopia are not equipped with adequate IT facilities including reliable internet access, which make it difficult to use this app if connection to a server is required at the beginning and end of every test.

Glaucoma Easy Screener (GES) is a smartphone VR visual screening tool designed based on a contextual inquiry [90] of eye care in Ethiopia, one of the low income countries where glaucoma is among the major causes of blindness [169]. There was a good level of acceptance among Ethiopian ophthalmic professionals to use GES for quick screening, after experiencing its early prototype with patients [60]. The aim of this pilot validation study is to assess accuracy of GES by comparing its results with the gold standard Octopus perimeter.

5.2 Materials and Methods

5.2.1 Participants and Test Procedure

The study was conducted at the ophthalmology department of the University Hospital of KU Leuven. A total of 33 healthy participants (10 male, 23 female), the same participants that were recruited for normative database development (see Chapter 3, p45), were also asked for the assessment of agreement, after written informed consent has been received. As visual field sensitivity is known to decline with age [116], participants from a wide age range were recruited. Each participant underwent a complete ophthalmic examination, including visual acuity testing, auto refractometry, bio microscopy, non-dilated funduscopy and visual field screening with Octopus GST. Inclusion criteria for all healthy participants were best-corrected visual acuity of 20/20 for patients under 55 years and 20/25 for patients 55 years or older, intraocular pressures between 10 and 21 mm Hg, normal optic discs and fundus appearance and not missing more than one location on the Octopus GST screening test.

5.2.2 Assessment of Agreement with Octopus GST (Gold standard)

In order to assess agreement between GES and Octopus GST, all participants for the normative database development were invited again for a screening test with GES. Visual field screening with GES was performed for 36 eyes of 18 participants who accepted the second invitation. Values which correspond to the 95 percentile (P-95) of the participants for each age group (in range of 5 years) were used as a screening criteria for each location. Failing to detect a stimulus that can be detected by 95% of the normal participants of that age group is considered as a visual field defect for that specific location.

5.2.3 Data Analysis

Level of agreement between GES and Octopus GST was computed for the 36 eyes that completed both screening tests. As the outcome of the test for each location is a dichotomous data point (seen or missed), the results for each eye with both GES and GST were encoded with “1” for seen and “0” and missed locations respectively. Data were then imported to IBM SPSS 25 software for analysis. It was not possible to compute a Kappa coefficient as most of the data from normal participants were constant, with all data locations seen. Hence, a simple percent agreement was computed for each eye based on the

number of seen and missed locations. Simple percent agreement was also computed for each of the 28 locations, across all participants.

5.3 Results

5.3.1 Normative Database

Participants age ranged from 22 to 58 years, with an average of 31.7 (SD 11) years. Four eyes out of the 66 were excluded due to missing more than one location out of the 28 locations in the Octopus GST. Threshold sensitivities for the 28 locations were obtained from the remaining 62 eyes. The average sensitivity across all patients is around 20 dB while the minimum sensitivity varies between 11 and 19 dB. As shown in Figure 5.1, the maximum sensitivity for most of the locations is 25 dB. The highest sensitivity, which corresponds to the dimmest stimulus that can be detected on the smartphone, is 27 dB. The lowest sensitivity, which corresponds to the brightest stimulus presented to be detected by the participants, is 11 dB.

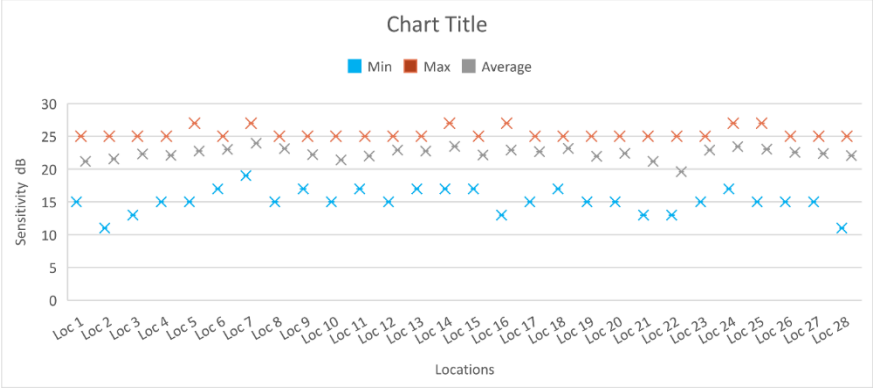


Figure 5.1 Minimum, maximum and average threshold sensitivities in dB across all participants for the 28 locations.

The average sensitivity of 28 locations shows a slight decrease with increasing age as shown in Figure 5.2.

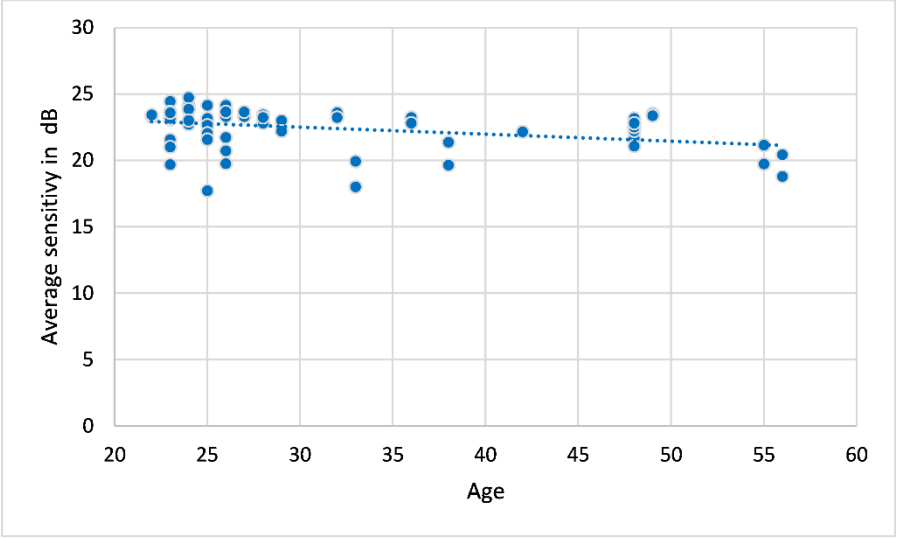


Figure 5.2 Average sensitivity of 28 locations, with respect to age. Each dot represents an eye. The dotted trend line shows the decrease in average sensitivity with increasing age.

5.3.2 Agreement with Gold Standard (Octopus)

Figure 5.3 shows the percent agreement computed for each of the eyes by comparing the number of seen and missed locations. Out of the 36 eyes, there was 100% agreement for 17 eyes, 90-99% agreement for 11 eyes, 80-89% agreement for 4 eyes and 4 eyes had agreement below 80%, with lowest agreement value being 64%.

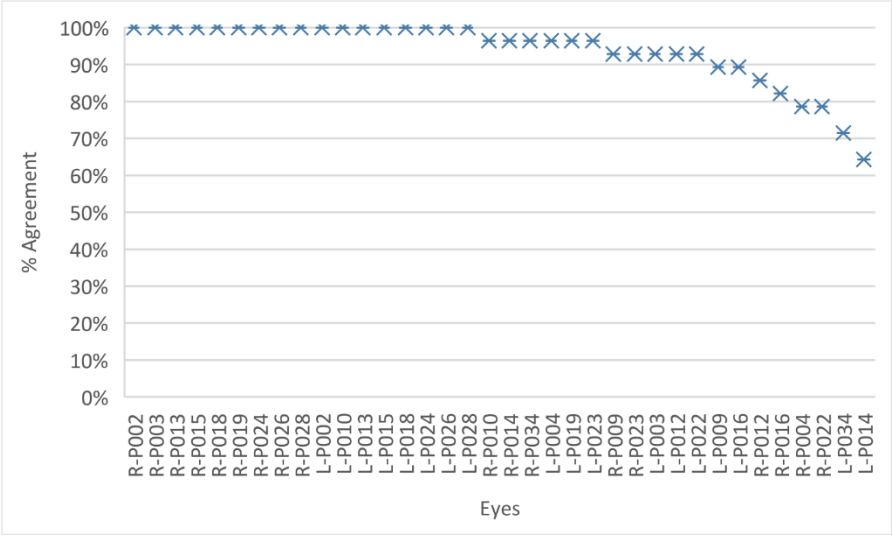


Figure 5.3 Percent agreement between GES and Octopus based on number seen and missed locations for each eye.

Figure 5.4 shows the percent agreement for each of the 28 locations by comparing the number of eyes having the same result (1 vs 1 or 0 vs 0) for each of the locations in both tests. There was 90-100% agreement for 19 locations, 80%-89% agreement for 8 locations, and 78% agreement for one location. Average test duration per eye was 1.1 (SD 1.0) minutes with Octopus GST, and 1.9 (SD 0.2) minutes with GES.

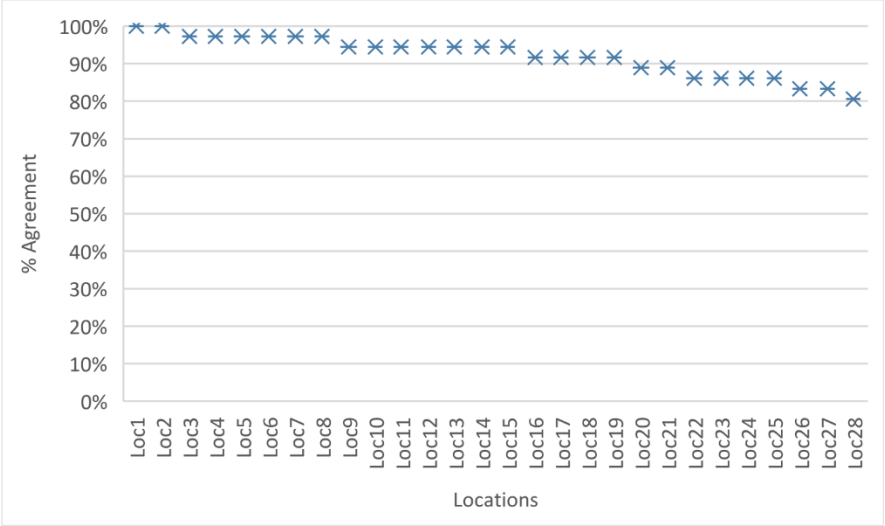


Figure 5.4 Percent agreement between GES and Octopus for the 28 locations.

5.4 Discussion

GES is intended to be used as a low-cost and portable glaucoma visual field screening tool for remote areas using a smartphone, VR headset and gaming joystick. The screening app running on the smartphone was designed based on a glaucoma screening test available on the Octopus perimeter. After normative database development, agreement between GES and Octopus GST was assessed by comparing test results of participants who completed both tests. There was a good level of agreement between GES and Octopus GST, which indicates GES has potential to provide reliable glaucoma screening results; . Consequently, GES may improve accuracy of referral decisions in remote areas, where there is no access to standard perimetry equipment.

While assessing agreement between two measurements dealing with dichotomous data (seeing or missing a stimulus in our case), the Kappa statistic is the preferred method, as it compensates for agreement by chance [170]. However, since all the participants for the assessment of agreement were among those recruited for the normative database, most of them never missed stimuli during either test. Results for most of the locations were constant (all data locations were seen), therefore not fulfilling the assumption for the Kappa statistic. An improved assessment of the agreement between GES and Octopus GST could be done by recruiting glaucoma patients. With

a sample of participants with impaired visual fields, more locations will be missed which will give non-constant data to compute the Kappa coefficient.

In the current study, agreement between GES and Octopus was assessed by recruiting normal participants. Though the good level of agreement achieved during this study provides supports the reliability of GES test results, its performance in detecting glaucoma cases cannot be determined merely based on these results. For screening tests, assessment of sensitivity and specificity is an additional key step before clinical use [171]. Therefore, a separate study was conducted to assess sensitivity and specify of GES (see Chapter 6), by recruiting normal participants and glaucoma patients.

This study has a number of limitations. Firstly, this pilot study has a small sample size. GES's agreement with Octopus GST was assessed with 36 eyes of normal participants. Hence, no major conclusions can be made about its clinical accuracy for community wide screening. Based on the promising results from this pilot study, it is worth further testing GES's accuracy with a bigger sample. This future validation study should include glaucoma patients with mild to advanced visual field defects and normal participants. Secondly, the normative database for GES was constructed from data of 62 eyes of 33 participants. This may be considered a low number, compared to the number of participants for database construction in standard equipment like Humphrey and Octopus [172]. A more representative normative database can be constructed in the future by recruiting more participants from various age groups.

5.5 Conclusion

This study demonstrated GES's potential as a low-cost and portable visual field screening device for situations where standard perimetry equipment is not available. It exhibited a high level of agreement with the clinically recognized gold standard Octopus perimeter. The promising results from this pilot study motivated implementation of a validation study with a larger sample size. Further improvement is required to improve fixation monitoring, test progress monitoring and size of its normative database.

Chapter 6

Sensitivity and Specificity of Glaucoma Easy Screener

This chapter is submitted to EAI Endorsed Transactions on Pervasive Health and Technology Journal.

Abstract

OBJECTIVES: The aim of this study is to assess the sensitivity and specificity of GES.

METHODS: We recruited 35 participants : 80% (28) M and 20% (7) F. The mean (SD) age was 49.8(17.3) years. 22 were glaucoma patients and 13 were normal subjects. Receiver-operating-characteristic (ROC) curve was used to assess sensitivity and specificity of GES.

RESULTS: The area under the ROC curve was 0.91 (95% confidence interval, 0.83 to 0.99 P<0.001). Picking 3 missed points as a cut-off point yielded a sensitivity of 90% and specificity of 85%.

CONCLUSION: GES has shown good sensitivity and specificity in detecting glaucoma. A cut-off value of 3 missed points or 4 missed points can be used with an acceptable trade-off between sensitivity and specificity. Further study of larger patient population is required to assess GES's sensitivity and specificity.

6.1 Introduction

Glaucoma is the leading cause of irreversible blindness worldwide [173], [174]. The number of people with glaucoma is projected to reach 111.8 million in 2040 [175]. Large proportion of these glaucoma cases will be from developing countries in Asia and Africa [175]. In the absence of screening, most patients with glaucoma remain undiagnosed until advanced disease is present due to the asymptomatic nature of glaucoma, especially in its early stages [176], [177]. About 70% of glaucoma patients in developing countries are unaware of the disease [177], [178]. Glaucoma is a treatable disease, and the early detection and treatment of glaucoma reduces visual loss. As glaucoma is a treatable disease, early detection is critical to prevent further damage to vision. Screening therefore plays a key role in preventing blindness due to glaucoma. Screening has been shown to detect glaucoma at earlier stages when compared to cases detected solely on patient presentation to the clinic [179], [180].

Visual field testing (VFT) is one of the major tests for screening and diagnosis of glaucoma [73]. The test assesses central and peripheral vision of each eye separately in order to detect vision loss, which, in case of glaucoma, gradually progresses from the periphery to the center. The test is mostly performed with standard automated perimetry (SAP) equipment which is expensive and not easily portable [48], [181]. Glaucoma Easy Screener (GES) was designed to be a low-cost and portable visual field screening tool. It comprises of a smartphone, stereoscopic headset and a gaming joystick. The screening mobile application was developed based on the glaucoma screening test (GST) available in the Octopus perimeters (Haag-Streit AG, Köniz, Switzerland) [101]. The test takes less than a minute for normal participants and up to 1.5 minutes for patients with advanced glaucoma [102].

GES's acceptability among ophthalmic professionals and patients was assessed at four hospitals in southwest Ethiopia. A pre-post design was followed to assess ophthalmic professionals' perspectives towards GES before and after use [182]. Ophthalmic professionals perceived GES as easy-to-use, enabling the screening of glaucoma screening tests, especially during outreach to rural areas. Even older patients from rural areas, with limited familiarity with technology, were able to perform the test with GES. However, a concern raised by ophthalmic professionals during this study was the need to determine sensitivity and specificity of GES before clinical use.

Sensitivity and specificity are the two measures commonly used to evaluate performance of screening tests [183], [184]. Visual field test strategies incorporated in gold standard equipment and other glaucoma tests are evaluated based on these two major parameters [185], [186]. The sensitivity of a screening test refers to its ability to properly identify people with a disease condition (true positive). In contrast, the specificity of the test reflects the probability that the screening test will be negative among those who, in fact, do not have the disease [187]. The purpose of this study is to assess the sensitivity and specificity of GES and discuss the results within the context of glaucoma screening.

6.2 Materials and Methods

6.2.1 Participants

Recruitment involved 35 participants : 80% (28) were male and 20% (7) were female. The mean (SD) age was 49.8(17.3) years. Out of the 35 participants, 22 were glaucoma patients under regular follow up in the glaucoma clinic of the ophthalmology department and 13 were normal subjects among hospital staff. Informed consent was received from all participants before performing tests. Glaucoma patients were selected by an experienced ophthalmologist based on an already established glaucoma diagnosis including Humphrey visual field test before the screening tests were performed. From the 22 patients, 40 eyes with mild to moderate glaucoma cases were included as those with advanced glaucoma may not be able to perform visual field test due to poor fixation. Inclusion criteria for all healthy participants were best-corrected visual acuity of 20/20 for patients <55 years and 20/25 for patients 55 years or older, intraocular pressures between 10 and 21 mm Hg, no visual field loss on Humphrey visual field test and normal optic discs and fundus appearance. From the 13 normal participants, 20 eyes were included based on the inclusion criteria. All participants performed screening test with GES.

The study was conducted at the ophthalmology department of the Jimma University Medical Center tertiary hospital in the town of Jimma, Ethiopia. The research followed the tenets of the Declaration of Helsinki and was approved by the ethical review board of Jimma University Institute of Health.

6.2.2 Data Analysis

The major criteria that can be used to categorize normal vs glaucomatous results is the number of missed points. A test result will be considered

glaucomatous if the number of missed points is above a given value, called the cut-off. Results with number of missed points below this cut-off value will be considered normal while those equal to or above the cut-off value will be considered glaucomatous. Therefore, the score for GES is based on the number of missed points for each eye. The reference gold standard is based on clinical diagnosis including Humphrey visual field test with dichotomous output, glaucomatous/normal. Capacity of GES in identifying glaucomatous visual fields was assessed using receiver-operating-characteristic (ROC) curves. The ROC curve is a plot displaying the full picture of trade-off between the sensitivity and (1- specificity) across a series of cut-off points [188]. Area under the ROC curve(AUC) is considered as an effective measure of inherent validity of a diagnostic test [189]. An ideal test would have an AUC of 1.0, whereas a test with no discriminative ability would show an area of 0.5 [189], [190]. AUC of 0.7 to 0.8 is considered acceptable, 0.8 to 0.9 is considered excellent and above 0.9 is considered outstanding [191]. The optimal cut-off point that would yield the best combination of sensitivity and specificity can also be determined from the coordinates of the curve. SPSS software was used for data analysis.

6.3 Results

The ROC curve was plotted with sensitivity on the y-axis and 1-specificity on the x-axis. The area under the ROC curve was 0.91 (95% confidence interval , 0.83 to 0.99 $P<0.001$) (see Figure 6.1). This result (AUC above 0.9) shows the strong discriminating ability of GES between normal and glaucomatous eyes.

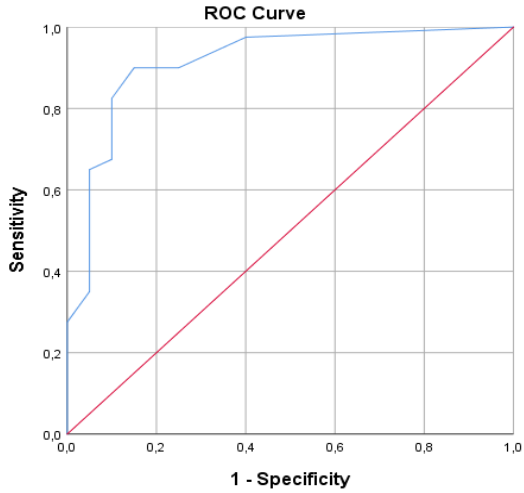


Figure 6.1 ROC curve for various cut-off values of number of missed points with GES screening test.

Sensitivity and specificity of GES varies for various cut-off values as shown on Table 6.1. For instance picking 3 missed points as a cut-off point for categorizing the result as glaucomatous yields a sensitivity of 90% and specificity of 85%. A cut-off point of 4 missed points on the other hand yields a sensitivity of 83% and specificity of 90%. Cut-off values, ranging from 6-10 missing points are not candidate values, as sensitivity only decreases without affecting the specificity (see Table 6.1).

Table 6.1 Sensitivity and specificity of GES for various cut-off values (from coordinates of the ROC curve).

Number of missed points	Sensitivity	Specificity
1	98%	60%
2	90%	75%
3	90%	85%
4	83%	90%
6	80%	90%
7	78%	90%
8	75%	90%
9	73%	90%
10	68%	90%

6.4 Discussion

The major aim of this study was to assess sensitivity and specificity of GES as a low-cost and portable glaucoma visual field screening tool. The study demonstrated GES's good performance in accurately discriminating between normal and glaucomatous eyes based on the area under the curve (0.91). Furthermore, the optimal cut-off point to demarcate the threshold number of missed points to classify normal and glaucomatous results can be determined from the coordinates of the curve, and suggest values between 3 and 4. Specifying this value is helpful for ophthalmic nurses in rural health centers who might not have adequate ophthalmic training to distinguish between normal and glaucomatous GES screening results to make referral decisions.

However, the sensitivity and specificity of a test vary along with the cut-off point to be chosen and are highly dependent on the clinical context [188], [192], [193]. There needs to be a balance between sensitivity and specificity so that neither of them is too high or too low [194]. The specificity requirement of screening tests is relatively lower compared to diagnostic tests since there will be follow up confirmatory tests following positive screening results [195]. GES is mainly designed to be used in remote areas of developing countries where there is limited access to eye care. In some areas, like southwest Ethiopia, regular eye care is covered through outreach missions, which are organized once or twice a year [48]. Ophthalmic professionals from tertiary hospitals could incorporate visual field screening into their comprehensive eye examination as they GES can easily be carried. Getting the chance for comprehensive eye examination during these missions is often a challenge due to the large number of people queuing up. If the sensitivity of GES is too low, high number of people will be falsely identified as normal and will not be referred for further diagnosis. Missing 3 points is an optimal cut-off value in such situations giving a sensitivity of 90% and specificity of 85%. On the other hand, if GES is to be used in situations with better access to eye care where people can get regularly regular check-ups, missing 4 points may be a better cut-off value giving sensitivity of 83% and specificity of 90%.

Previous studies have also demonstrated validity of head mounted visual field screening devices for glaucoma screening [54], [196]. Results of this study further reinforces the clinical validity of low-cost VR for visual screening. In this study, we were only able to test 60 eyes of 35 subjects. As highlighted in other studies [54], [190], a study of larger patient population is still required

to determine the validity of GES for community wide glaucoma screening. If adequate data is obtained from such a study, machine learning algorithm could also be incorporated in the screening app to assist health workers with limited ophthalmic training in identifying glaucomatous visual field results.

6.5 Conclusion

GES has good sensitivity and specificity in detecting glaucoma. A threshold cut-off value of 3 missed points or 4 missed points can be used with an acceptable trade-off between sensitivity and specificity. Further study of larger patient population is required to assess GES's sensitivity and specificity for community wide screening.

6.6 Acknowledgements

We would like to thank staff members from the ophthalmology department of Jimma University Medical Center and Reyan Ophthalmology clinic for their support during this study.

Chapter 7

Conclusion and Future Work

As mentioned in the introduction, glaucoma is a "silent thief of sight", leading to irreversible blindness if not detected and treated early. There is a dire need for low-cost and portable methods for the detection of the disease, given the asymptomatic nature of the disease. In this thesis, we investigated the design and development of a low-cost and portable visual field glaucoma screening tool using a smartphone and a VR headset. This concluding chapter first revisits the research objectives and reflects on the scientific contributions made during this doctoral study. We end this chapter with suggestions for future work.

7.1 Revisiting the Research Objective and Research Questions

Objective: to assess the feasibility of a low-cost and portable visual field screening platform, using a smartphone and VR headset, for the early detection of glaucoma in rural areas of developing countries.

RQ1: What are the needs and preferences of ophthalmic professionals and patients in rural areas of developing countries towards a visual field screening platform using smartphone and VR headset?

This research question was addressed through a contextual inquiry of eye-care in developing countries where we studied current methods of glaucoma detection and treatment. Semi-structured interviews were conducted with ophthalmic professionals at three different hospitals in Southwest Ethiopia (see Chapter 2). Observations were made during regular consultation hours and an outreach field mission in one of these hospitals.

Applying an inductive thematic analysis process [58] of interview and observation data, seven major themes were identified i.e. "tertiary health care to provide primary eye health care", "outreach programs and NGOs", "glaucoma is too invisible to be a priority", "lack of prevalence data", "problematic patient data storage and retrieval", "manual copying of test results", "visual Field Testing is challenging for patients and nurses". Three additional themes were added following further analysis of the previous themes, which were formulated as paradoxes i.e. "money is not an issue, yet there is no money for glaucoma", "shortage of eye health care, yet the work is repeated over and over", "the willing but uncooperative patient tested by the willing but unexperienced nurse".

This contextual inquiry elicited key requirements pertinent to design decisions to be made to address needs of ophthalmic professionals and patients. Primary health facilities which are easily accessible to the rural population do not

provide even basic eye care services mainly due to lack of OPs and diagnostic equipment. For a smartphone based visual screening tool to be effectively used in such areas, it should require minimal to no ophthalmic training to perform the test and interpret the results for referral decision.

The eye care service largely relies on funding from NGOs, which usually focus on cataract and Trachoma Trichiasis due to lack of prevalence data. The NGOs are not expected to support glaucoma efforts in the coming years until cataract and TT are effectively addressed, which will practically take years, if not impossible. Hence the cost of owning and using a smartphone based visual field screening tool should be kept as low as possible to allow rural health facilities acquire it even without support from NGOs.

The existing paper-based patient-record keeping system is not expected to be automated any time soon. Ophthalmic professionals are well accustomed to paper works. They expect a paper test result printout, even from a smartphone application. Synching results with an electronic medical record system is not an option. A smartphone based visual field screening tool should be designed to present test results on the smartphone display in a manner that can quickly be understood and interpreted by even non-ophthalmic professionals at primary level health facilities.

Any patient needs to get detailed orientation of how to perform a visual field test with the standard perimetry equipment. This is a known challenge, even for patients in developed countries familiar with technology devices. In light of the challenges ophthalmic professionals face to supervise patients with the standard perimetry equipment for patients from rural areas, a smartphone based visual field test tool should integrate a much more easier method to allow health professionals explain the test.

Finally, a key constraint that will affect all the aforementioned needs, is the time constraint to screen a single patient due to the high health professional to patient ratio. This is much more critical during outreach field missions. A smartphone based visual field screening tool should be designed to perform quick tests.

RQ2: How do we design and develop a mobile app for visual field screening tailored to the needs of ophthalmic professionals and patients from rural areas?

Design decisions were made to address the technical, functional and contextual requirements followed by development of the Android app. An appropriate screening strategy that fits requirements of ophthalmic professionals was adopted from a gold standard equipment (see Chapter 3). This strategy comprises of 28 locations spread across the visual field. These locations were lie on nerve lines typically affected by glaucoma making the strategy more appropriate for glaucoma screening. The test takes an average of 1 minute per eye on the standard device. This is an ideal fit to the contextual requirement to shorten the test durations as much as possible.

The strategy presents test results in a simplistic manner with seen and points clearly demarcated with symbols which enables health professionals without ophthalmic training to understand the result with little orientation.

The smartphone display was calibrated to guarantee accurate control of stimulus luminance similar to gold standard equipment. The luminance range of the smartphone display was determined from the calibration. The mobile app manipulated pixel RGB values based on these parameters to present stimuli at varying intensity values as per the screening strategy selected.

Test parameters such as stimulus duration, response time and reliability indices were incorporated in accordance with the requirements in gold standard equipment. Fixation loss and false positives which are the key reliability indices in standard perimetry were incorporated. For the purpose of this study we adopted acceptable fixation loss and false positive values from standard perimetry equipment. Further study is required in the future to determine cut-off values appropriate for a portable screening platforms similar to GES.

Since a screening test relies on a reference database of normal people, a normative database was developed by capturing sensitivity values from normal participants (62 eyes). Though it was not possible to incorporate normative database of the same size as the standard equipment, we strongly consider this as a strength of this PhD work since other related works on portable visual field tools using tablets or smartphones do not incorporate a normative database.

The screening Android app was developed incorporating the above design parameters maintaining simplistic interaction for ease of use. The number of screens/activities was kept minimal to minimize time required to interact with the app. The simplicity will also help health professionals to easily use the app with few quick steps.

RQ3: What are ophthalmic professionals' use and acceptance of a glaucoma screening platform using smartphone and VR headset?

An adoption study was conducted with 19 ophthalmic professionals from four hospitals in Southwest Ethiopia. A pre-post study design was adopted to assess OP's perspective towards GES (see Chapter 4). OPs filled Likert scale questionnaire based on the Unified Theory of Acceptance and Use of Technology (UTAUT) before using GES (pre-use) and after using GES with patients (post-use).

There were significant improvements in the scores post-use items compared to pre-use for all UTAUT constructs. This indicates that ophthalmic professionals found GES to be more useful and easy to use compared to their expectations before using it.

OPs perceived GES as easy-to-use, enabling the screening of glaucoma screening tests, especially during outreach to rural areas. Even older patients from rural areas, with limited familiarity with technology, were able to perform the test with GES, and valued a 'technical' assessment. Nevertheless, the need for a further assessment of its sensitivity and specificity was frequently stressed by OPs. OPs also raised a particular concern regarding possibility of the tool being misused for diagnosis instead of screening, especially by non-ophthalmic health professionals in remote areas due to lack of adequate ophthalmic training on glaucoma diagnosis and treatment.

RQ4: What is the accuracy of a glaucoma screening platform using smartphone and VR headset compared to a gold standard perimetry equipment?

As stressed by OPs during a use and acceptance study, GES's accuracy should be assessed before clinical use. A study to assess GES's agreement with gold standard perimetry equipment was conducted at the ophthalmology department of the University Hospital of KU Leuven (see Chapter 5). A total of 18 participants (36 eyes) performed screening test both with GES and gold standard equipment and level of agreement between the two results was analysed. There was a good level of agreement (above 85%) between GES and the gold standard. Results from this study demonstrated potential of GES to provide reliable screening results while maintaining minimal cost and portability.

RQ5: What is the sensitivity and specificity of a glaucoma screening platform using smartphone and VR headset?

The screening test strategy adopted by GES incorporates 28 locations with a patient either seeing or missing stimuli at each of these locations. A cut-off criteria based on the number of points missed to designate glaucomatous results needs to be determined. A total of 40 glaucomatous eyes and 20 normal eyes were tested with GES (see Chapter 6). Receiver Operator Characteristic (ROC) was used to determine an optimal cut-off points that yields the best combination of sensitivity and specificity. A cut-off value of 3 missed point yielded an acceptable trade-off between sensitivity (90%) and specificity (85%).

7.2 Scientific Contribution

A major challenge to the successful adoption of mHealth solutions in low-resource settings is lack of tailoring design and development to the actual context. There is an increased risk of failure when if mHealth solutions are not designed for or adapted to the specific context [197]–[199]. Challenges unique to low-resource settings such as inadequate infrastructure, shortage of health professionals and cultural influences need to be well understood from the initial inception of design. Using user centered design principles for the design of mHealth apps allows developers to grasp user needs at early stages of the development [200], [201]. In this PhD study, we followed a UCD model for mHealth applications that enabled us to grasp the unique needs of OPs and patients in developing countries. Through the contextual inquiry of eye care in the actual context, we identified key requirements that complemented technical and functional requirements which we later translated into design decisions. We conducted part of this study, such as assessment of agreement with gold standard, in Belgium, where there is adequate access to expertise and equipment to handle technical and functional requirements. Part of the study to identify contextual needs and assess use and acceptance were conducted in Southwest Ethiopia. We hope the UCD approach we followed in this research can guide future mHealth initiatives for screening and diagnosis where there is a need to address both contextual and functional accuracy requirements.

A number of mHealth applications have been introduced for screening infectious diseases such as COVID-19, Ebola, Severe Acute Respiratory Syndrome (SARS), HIV, and others in low-income countries [202], [203]. Numerous mHealth interventions flourished in many countries during the COVID-19 outbreak for case detection and contact tracing. mHealth

applications are also being used for screening non-infectious diseases like cancer, hypertension and diabetes in low-income countries [204], [205]. A recent study on the effectiveness of mHealth for access to eye care in Kenya found that non-ophthalmic health professionals at primary level can easily identify and refer cases which enables to ease the burden at the secondary and tertiary levels [206].

This PhD work adds further piece of evidence to the feasibility of mHealth applications for screening in low-income countries such as Ethiopia. The encouraging results obtained both from the accuracy and usability studies strengthen the findings from multiple studies on the potential of mHealth for screening and diagnosis in low-income countries.

Most of the recent studies on virtual reality and/or smartphone based visual field test technology are conducted in high income countries. Home-based self-screening and follow-up using VR visual field is discussed in some of these studies [207]. The findings from this PhD study clearly show that home-based self-tests with such technology is almost impossible in the context of low-income countries like Ethiopia due to economic challenges in affording this technology and low literacy rate among the rural population. Any mHealth intervention for screening of diseases in rural areas of low-income countries should consider use of these technology with close supervision of health professionals.

Another major contribution of this PhD work is the clinical validation process followed throughout the study to achieve an acceptable level of accuracy. A growing concern with the proliferation of mHealth apps is lack of regulation to validate their diagnostic accuracy. Studies conducted on some mHealth apps have revealed wider accuracy gaps as they were not clinically validated using established evidence-based guidelines [208]–[210].

In this PhD study, we followed rigorous steps to guarantee clinical validity of GES's screening results beginning from the development of a normative database, assessment agreement with the gold standard, and sensitivity and specificity. We conducted various tests on normal participants and glaucoma patients following strict clinical validation protocols with the support of glaucoma experts.

Another common gap in mHealth literature next to clinical accuracy, is the absence of empirical evidence on usability and acceptability among the target users in the actual context of use [211]. As to our knowledge, none of the

recent studies on smartphone based and virtual reality based visual field test included usability assessments. In this PhD study we conducted an assessment usability and acceptability of GES among ophthalmic professionals which augmented the clinical accuracy assessments.

mHealth applications are recently gaining more attention due to the COVID 19 pandemic, for screening and contact tracing [212]. The pandemic situation further stimulated use of mHealth for other problems like mental health monitoring due to the lock downs [213]. However, most of these recent applications of mHealth are in developed countries. Low-income countries can easily catchup with the rest of the world in the implementation of mHealth applications given the increased affordability of smartphones and expansion of mobile network coverage.

Future mHealth initiatives for rural areas of low-income countries should focus both on clinical accuracy and usability. Following the adopted user centered design model we followed in this PhD research will address these two major gaps in mHealth interventions. Engaging health professionals and patients in the actual context throughout the design and development process would highly improve their usability and acceptability. As repeatedly discussed in this PhD manuscript, people from rural areas of low-income countries have limited exposure to technology devices and find it more difficult to adopt to technology compared to those in developed countries. Even though focusing on both clinical accuracy and usability at the same time might have resource implications, it will significantly improve the successful adoption of the applications.

7.3 Future Work

7.3.1 Broadening and Diversifying the Normative Database

The procedure for setting up a normative database was described in Chapter 3. The reference database was constructed from 62 eyes of 33 (average age 31.7) normal participants. Compared to the gold standard equipment, this is a relatively low number. It was not feasible to recruit larger number of participants within the scope of this doctoral study. Furthermore, most of the participants for the normative database construction were young (mostly in their early twenties). As visual sensitivity is known to decline with age and glaucoma mostly affecting people aged above 40, the normative database should include more participants aged above 40. Hence future improvements of GES should incorporate a broader normative database with larger number of participants of varying age.

7.3.2 Adoption Study based on Long-term Usage

The use and acceptance study presented in Chapter 4 was based on usage of GES. Multiple usability factors that could arise from long-term use were not considered in the study. An enhanced assessment of GES's use and acceptance among OPs could be done after allowing them to use the tool over a period of time. Furthermore, the use and acceptance study was mainly focused on OPs instead of patients. Though, much of the interaction with GES app is handled by OPs, further usability assessment from patients perspective is possible.

7.3.3 Further Assessment of Sensitivity and Specificity

Sensitivity and specificity are key parameters in the assessment of a screening tool. The study of sensitivity and specificity of GES presented in Chapter 6 was based data of 40 glaucomatous and 20 normal eyes. A more robust ROC analysis could be done to determine the ideal cut-off value for sensitivity and specificity if the cohort size for both glaucomatous and normal eyes is increased.

7.3.4 Potential Enhancements to the Screening App

The current version of the GES app can be enhanced in multiple ways. More suprathreshold screening algorithms could be incorporated in a future version to give more options to OPs. By synching patient data to a central server, OPs in rural health facilities could monitor disease progression based on distribution and number of missed points. Furthermore, machine learning features could be incorporated in to app to classify normal and glaucomatous test results.

To conclude, despite all these possible improvements, we acknowledge that the current version by itself could make a lot of difference in rural areas of developing countries like Ethiopia, where ophthalmic examination relies on primitive instruments like torch light.

Appendix A UTAUT Questionnaire

Usability of the platform(put a tick(✓) for the answer of your choice)-PRIOR						
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
PE1	This platform will be useful during outreach screening.					
EE1	I think the platform will be easy for me to administer visual field tests.					
SI1	I think the senior ophthalmologist staff will recommend the platform for glaucoma screening.					
FC1	All the necessary resources to use the platform will be easily available.					
BI1	If made readily available, I intend to use the platform in the near future.					
PE2	The platform will enable me to make more accurate diagnosis.					
EE2	I think learning how to use the platform will be easy					
SI2	In general, I think the platform will be seen as useful by the ophthalmology department.					
FC2	The platform will not be expensive for our clinic to purchase.					
BI2	When available, I would like to take the platform along with other kits for outreach mission.					
FC3	The platform can be used with our existing infrastructure					
SI3	My colleagues will support my use of this platform					
SI4	My patients will be open to the use of this platform					

Usability of the platform(put a tick(✓) for the answer of your choice)-PRIOR						
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
EE3	It will be easy to have patients wear the VR headset					
PE3	I do not expect that this platform can be used for a reliable eye exam.					
EE4	Compared to the FDT, administering visual field testing with this platform will be easier					
BI3	I am looking forward to using this platform when it is available.					
FC4	Charging the smartphone will not be challenge, even during outreach missions.					
SI5	If I use the platform, I will be considered as an advocate of technology by my colleagues.					
EE5	The platform will be easier for patients from rural areas compared to the FDT					
PE4	More glaucoma cases can be detected by the platform.					
EE6	Patients can easily use a joystick for response.					

Usability of the platform(put a tick(✓) for the answer of your choice)-POST						
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
EE1	The platform is easy for me to administer visual field tests.					
SI1	In general, I think the platform will be seen as					

Usability of the platform(put a tick(✓) for the answer of your choice)-POST						
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
	useful by the ophthalmology department					
FC1	All the necessary resources to use the platform are easily available.					
BI1	If made readily available, I will intend to use the platform in the near future.					
PE1	The platform will enable me to make more accurate diagnosis.					
EE2	It was easy to make patients wear the VR headset.					
SI2	My colleagues will support my use of this platform.					
FC2	Charging the smartphone will not be a challenge, even during outreach missions.					
BI2	I am looking forward to using this platform when it is available.					
EE3	Learning how to use the platform was easy for me.					
PE2	I do not expect that this platform can be used for a reliable eye exam.					
EE4	Compared to the FDT, administering visual field with this platform is easier.					
SI3	If I use the platform, I will be considered as an advocate of technology by my colleagues.					
FC3	The platform cannot be used in the current setting.					

Usability of the platform(put a tick(✓) for the answer of your choice)-POST						
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
BI3	I would like take the platform along with other kits for outreach mission, when available.					
EE5	The platform is easier to use with patients from rural areas compared to the FDT.					
PE3	More glaucoma cases can be detected by the platform.					
EE6	Patients could easily use the joystick to give their response.					
SI4	The senior ophthalmologist staff is likely to recommend the platform for glaucoma screening.					
FC4	The platform is not expensive for our clinic to purchase.					
EE7	My interaction with the platform was clear and understandable.					
PE4	The results presented are informative enough to make referral decisions.					
FC5	The platform can be used with our existing infrastructure.					
PE5	This platform will be useful during outreach screening.					
SI5	My patients will be open to the use of the platform.					

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