Validation of selected iPhone Optometric screening applications in vision screening

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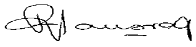
DECLARATION

I, Miss Therisha Moodley, declare as follows:

1. That the work described in this thesis has not been submitted to UKZN or any other tertiary institution for purposes of obtaining an academic qualification, whether by myself or any other party.
2. This dissertation is my own, unaided work and was supervised by Dr. R. Hansraj and Mrs. P. Govender.
3. My contribution to the research was as follows:
    - Concept, Design and Definition of intellectual content,
    - Literature search,
    - Clinical study,
    - Data collection, Data analysis and Statistical analysis,
    - Manuscript preparation,
    - Manuscript editing and review

Signature  Date: 04 December 2020

As the candidates' supervisors we agree to the submission of this thesis:

Prof R Hansraj  Date: 2 December 2020

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DEDICATION

I would like to dedicate my thesis to my parents for their never-ending support, encouragement and belief that I can achieve anything with hard work and dedication.

I am additionally grateful and would like to express my sincere appreciation to my lecturer/ supervisor and role model Prof. R Hansraj, for her valuable time, advice and continuous support throughout my degree.

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ABSTRACT

Introduction

There has been an unprecedent increase in the use of mobile technology to provide health care services. The eye care industry has also adopted the use of these innovative smart-technology devices to provide rapid, convenient and less time-consuming eye screenings through the use of applications (apps) however, the accuracy and reliability of these tests have not been fully established.

Aim

To determine if the selected smartphone apps have comparable results to their equivalent standard clinical optometric tests.

Method

The study employed a comparative research design that compared the results of two each, smartphone distance visual acuity (DVA), contrast sensitivity and astigmatism apps to the results provided by the standard Snellen DVA chart, Pelli-Robson chart and JCC test, respectively. A total of 113 participants were recruited using convenience sampling. The results were analyzed and the Wilcoxon Signed ranked test was used to assess for any comparisons.

Results

The median DVA as determined by the Snellen test and both VA apps were found to be exactly the same (0.63) for both the right and left eyes. More participants passed the CS test with the smartphone apps as compared to the standard Pelli-Robson test. Statistically significant ($p<0.001$) lower percentages of participants were detected as having astigmatism by both smartphone apps when compared to standard clinical testing.

Conclusion

The Kay iSight professional (paid) and Pocket Eye Exam (free) VA app testing, overall, showed promising results as they produced results similar to the standard Snellen test. Both the CS smartphone apps overestimated the results and both astigmatism apps significantly underestimated the number of participants with astigmatism. These apps therefore failed in providing accurate screenings results and need to be further modified before it can be used as a screening device. However, due to the lack of literature more studies need to be done before these devices can be used for home screenings or clinical use.

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Rapidly advancing technology enabled the healthcare landscape to undergo dramatic changes over the past few decades. The use of technology to deliver health care services from a distance, often referred to as telemedicine (Alexander *et al*., 2011) is one such initiative, which has demonstrated to be an efficient way of delivering health care despite challenges in underdeveloped areas (Scott., 2016). With telemedicine, healthcare providers can assess, diagnose and treat certain medical conditions without the patient being physically in front of them often with the use of a range of technological devices such as computers, smartphones, videos and software applications (apps) (Smith, 2018).

The eye care industry, including both ophthalmology and optometry has, to an extent, adopted this approach to offer their services to a larger consumer base. Teleophthalmology has been used to successfully screen diabetic patients, as well as, to manage and monitor patients with glaucoma and age-related macular degeneration using apps such as the "ZEISS Diabetic Retinopathy Screening Reading App" (Microsoft, 2015) and the "Amsler grid app" (All about vision.com., 2018). In addition to digital technology being used for clinical assessments linked to ocular pathology, there are currently numerous vision screening apps on the market that can be used to assess visual acuity (VA), contrast sensitivity (CS), astigmatism, stereopsis, colour perception as well as macular integrity, amongst others. These apps can be used for both clinical and self-assessments. In the eye care industry, this gives rise to a fairly new but rapidly advancing area of optometry known as Smartphone app screenings. These apps can be easily downloaded off the Google play and Apple app store as long as the smart device meets the specified requirements.

Smartphones have become very prevalent in today's developed world (Tofigh *et al*., 2015), with its various apps allowing multifunctional utility (smart vision labs., 2017). The term "mobile health care" is often used to describe delivery of health care with the use of these smart-tech devices, and this terminology will apply here onwards. The market for mobile health care has been growing steadily over the past few years and continues to do so (Medium., 2017). In 2016 there were approximately 259 000 health apps available on all major app stores and by the end of 2017 mobile health app revenue was expected to reach $26 billion (Medium., 2017). Furthermore, there are over 43,700 medical apps available in the Apple app store alone for physician and patient use (Vinay *et al*., 2015) and according to Jackson & Coker. (2011) approximately four out of five physicians were already using smart devices in their practices daily, with emergency room physicians (two

out of five) and cardiologists (one out of three) in particular, also frequently using digital technology in their medical practices.

Smartphones therefore currently, not only serve the purpose of communication but have advanced multiple functionalities with the ability to run advanced apps (Khanna., 2017). Moreover, in today's society individuals prefer to take care of their needs at their convenience resulting in the self-service industry growing significantly in the last few years (Castro *et al*., 2010). Statistics reveal that, across all industries, 81% of consumers prefer self-service platforms to service their needs (Malik., 2016). In the airline industry, 70% of flights have been known to be booked online and around 95% of tickets are issued digitally as e-tickets (GOV.UK., 2014). The British have also been known to make 18.6 million banking transactions every week using their smartphones and with the subsequent automation of certain services this has resulted in a cost saving of 20% and improving customer satisfaction (GOV.UK., 2014). People today lead busy lives hence, there preference for smartphone visual screenings appeal to them because of its convenience and accessibility. In the field of optometry, smartphone and mobile apps give these individuals the opportunity to perform vision screening tests on themselves and provide them with instant feedback regarding their visual status including the possibility of requiring a full comprehensive eye examination with a registered optometrist.

The uptake and usage of smartphones have, not surprisingly, been unprecedented. In terms of eye and vision care, there are more people each day using these devices to perform visual screenings hence, the rapid popularisation of these devices. If these devices are accurate they could possibly be used to negate the lack of ophthalmic resources in remote areas (Khanna., 2017). This has been linked to the need for ophthalmic care and devices that are beneficial but also cost-effective. It is envisaged that in the long-term, smart technology may actually prove useful in reducing the global visual impairment rate which currently stands at 405 million by providing wider access to ophthalmic care (Bourne *et al*., 2017).

A variety of smart technology is available to screen both visual functions, as well as ocular health. Eye care practitioners use the app "Peek Retina®" to screen for retinal pathologies. The "My Scotoma®" app is based on the Amsler grid test and is used to assess macular integrity, while the "colour blind eye exam®" app screens for colour vision deficiencies. The afore-mentioned apps can be very useful as tools for the early detection and monitoring of ocular pathology resulting in improved analysis of ophthalmological findings as well as improved time efficacy (Tofigh *et al.*, 2015).

In the field of optometry, smartphone apps allow for vision screening and include tests for the assessment of VA, CS and astigmatism. The "Kay iSight pro®", "Eye test®" and "Pocket Eye Exam®" are apps used to provide distance VA measurement. Apps for the assessment of CS include the "Smart Optometry®", "Variable

Contrast Sensitivity test®" and "Vision Scan®" app. Astigmatism may be detected by the "Eye Meter®", "Eye Test®" and "EyeXam®" Smartphone apps.

Despite the vast utilisation of these apps in both the optometry and ophthalmology arenas there has been minimal investigation into the accuracy of these screening apps resulting in the reliability of these apps being questioned. To the best of the researcher's knowledge, there has been minimal investigation into the accuracy and reliability of apps for visual function optometric testing. Inaccuracy of test results would impact the apps usability as a screening tool. Vinay *et al*. (2015) asserted that even with the rapid expansion in smartphone app testing, only approximately 54% of medical apps available on iTunes are reliable healthcare apps. Moreover, only a small portion of optometric smartphone apps have had high quality research to test the credibility of the apps bringing its validity into question.

The optometry industry has always been subject to intense regulations to ensure that patients receive the best possible care with accurate diagnosis and treatment. Smartphone-based optometry testing should be no different, yet there are limited published studies on the accuracy and reliability of these apps (O'Niell *et al.,* 2016). Factors such as lighting, target distance and target size need to be controlled and properly calibrated in order to yield comparatively accurate results. Furthermore, minimal investigation has been done on the results produced by the visual function apps in comparison to those obtained with standard clinical tests. There are no known studies on astigmatism app screening and only one study by Habtamu *et al*. (2019) was focused on Smartphone CS testing. Therefore, while these apps serve as convenient and accessible vision screeners, their usage in the eye health sector has, in many instances, not been fully validated.

Therefore, the aim of this study is to determine if the results produced by a selection of iPhone apps for vision screening are comparable to that produced by the equivalent standard optometric tests.

The objectives more specifically are to:

i. determine the accuracy of the Eye test® and Vision Scan® iPhone applications for assessing distance visual acuity by comparing the results obtained to that produced by standard optometric distance vision assessment with a Snellen chart.

ii. compare the results produced by Smart optometry® and Vision Scan® iPhone applications for the assessment of contrast sensitivity to that obtained with a Pelli-Robson chart.

iii. compare the results obtained in the screening for astigmatism with the Eye test® and Test your eyes: Eyesight® iPhone applications to that obtained following a subjective refraction.

iv. report on the usefulness of smartphone applications for vision screening.

v. determine the subjects' views of smartphone application screening versus standard clinical testing.

vi. recommend ways in which this technology can be improved for optimal use, if so indicated.

The null hypothesis to be tested in this study is that the results produced by iPhone applications for vision screening are not comparable to that produced by the equivalent standard optometric tests.

1.2 CONCLUSION

Rapid advancements in the use of mobile technology to deliver health care is unprecedented. The use of smartphone apps can be used as an effective way of reducing certain health care barriers particularly in outlying rural settlements where access to ophthalmic care is limited.

Today, more than ever, people are also relying on their smartphones to take care of all their needs with individuals increasingly taking an active interest in personalised health care particularly motivated by convenience, affordability and accessibility. There are numerous smartphone apps available on the iStore and Google play store, however, considering the literature that was reviewed and the limited published literature on smartphone app screening, it is apparent that more research is required on the accuracy of smartphone vision testing before it can be used optimally for either screenings and/or clinical use.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter gives us a summary of the published and grey literature that was found with respect to mobile and smartphone technology as it relates to eye and vision care. A literature search was conducted using two main databases i.e., PubMed and Research Gate for peer review studies pertaining to smart technology optometry visual testing apps. A combination of keywords, such as smartphone technology, iPhone, applications, visual acuity, astigmatism, contrast sensitivity and vision screening, in the form of title words or optometry subject headings, were used in the search. Reference lists of all identified articles were cross checked to identify other relevant studies. Studies dealing with smartphone/smart technology VA, CS as well as astigmatism testing were included in the compilation of this chapter. A total of 17 articles published from 2013 up to 2019 were found and reviewed.

2.2 SUMMARY OF EXISTING LITERATURE ON VISUAL ACUITY AND CONTRAST SENSITIVITY USING SMART TECHNOLOGY

Even though there has been an accelerated utilisation of smart technology for visual screenings, there is a paucity of published studies on the validation of these smart-tech apps. It is extremely important that when an individual has a vision screening done the results that are produced are accurate and reliable to facilitate the most appropriate and effective treatment and management being administered for that particular case. The current study has focused on the screening of distance VA, CS and astigmatism using smart-tech apps. According to Nangia *et al.* (2018) VA measurement is one of the main parameters for assessing the quality and quantity of vision, and subsequently standard of life. Kamiya *et al.* (2014) asserted that CS testing can be useful in detecting subtle changes in subjective visual performance. It is known that astigmatism is a type of refractive error that leads to distorted and blurred vision resulting in difficulty perceiving fine details, as well as impacting on visual comfort (Mediline plus, 2016). Hence, these visual aspects (VA, CS and astigmatism) if assessed adequately can provide useful information in the initial assessment of a person's vision which has a ripple effect on their overall functioning in life. Table 2.1 is a summary of the 17 articles identified to provide pertinent information about the accuracy, reliability, validity as well as, the development of the different Smart-technology apps. No study was found that reported on the assessment of astigmatism with smart technology hence the limited discussion of this aspect in this chapter.

Table 2.1:A summary of visual acuity and contrast sensitivity smart-technology apps researched

Author/s & year	Study site & sample	Aim	Conclusion
VISUAL ACUITY			
1. Rono *et al.*, 2018	Kenya 20 863 participants	Investigate the effectiveness of Peek acuity® test.	Peek acuity® test proved to be accurate.
2. Bastawrous *et al.*, 2015	Kenya 300 participants	To design and validate a Smartphone-based VA test that is not dependent on familiarity with symbols or letters.	Peek Acuity® Smartphone test is capable of accurate and repeatable acuity measurements.
3. Brady *et al.*, 2015	Kenya 300 participants	Design and validate a Smartphone-based VA test.	Peek Acuity® showed good accuracy and repeatability.
4. De Venecia *et al.*, 2018	Paraguay 393 participants	Validate the Peek Acuity® mobile phone application.	Peek app® tends to overestimate VA.
5. Han *et al.*, 2019	China and Australia 150 participants	Describe the development and validation of a Smartphone-based visual acuity (VA) test "V@home®".	V@home® could accurately and reliably measure both distance and near VA and is well accepted by participants.
6. O'Niell and McAndrew., 2016	Australia 60 participants	Evaluate the assessment of distance VA using mobile technology devices against the Snellen 3m chart.	High level of agreement of VA results between the Snellen wall chart and both mobile technology devices.
7. Pathipati *et al.*, 2016	California, USA 128 subjects	Determine if Automated VA apps can be used as an alternative to standard tests.	BCVA with an app was more accurate than with a Snellen chart.
8. Pereira *et al.*, 2015	Australia 88 participants.	Evaluate a Smartphone- VA chart with a Snellen chart.	VA measurements not equivalent to standard test, further validation required.
9. Rhiu *et al.*, 2016	China 43 participants	Assess if iPad measurements of VA were in agreement with standard clinical tests of VA.	iPad-based app of VA showed similar repeatability to standard clinical test.
10. Tofigh *et al.*, 2015	Texas, USA 100 participants	Evaluate VA measurements using the Eye hand book® app compared to a near VA chart.	Eye hand Book® overestimates the near VA compared to conventional near VA.
11. Zhang *et al.*, 2016	China 120 Participants	Evaluated the accuracy of an app for the iPad tablet (Eye Chart Pro®) for VA testing.	iPad VA test is reliable for VA testing only when the Snellen VA is better than 0.1 (20/200).

Author/s & year	Study site & sample	Aim	Conclusion
CONTRAST SENSITIVITY			
1. Habtamu *et al.*, 2019	Ethiopia 147 participants	Develop and validated a Smartphone-based CS test (PeekCS®).	Peek CS® is a repeatable and rapid test, providing results that are highly comparable with the commonly used PRCS test.
2. Kollbaum *et al.*, 2014	Texas, USA 40 participants	Determining the accuracy of an iPad Pelli-Robson CS test (ridgevue.com®).	iPad test showed good repeatability when compared to the standard Pelli-Robson test.
3. Rodriguez *et al.*, 2014	Spain 42 participants	Design a new CSF test to be used on an iPad.	The best agreement was found between FACT and ClinicCSF® version2 in all spatial frequencies.
4. Dorr *et al.*, 2013	USA 4 participants	Develop and validate a computerized CS test on an iPad device	iPad results were indistinguishable from standard tests.
5. Kingsnorth *et al.*, 2016	Birmingham, UK 20 participants	Validate the accuracy and inter-test repeatability of the near and distance Aston CS® test.	Aston® near and distance apps are valid, repeatable and time-efficient for all spatial frequencies.
6. Zeri *et al.*, 2018	UK, Italy 32 participants	Evaluate the accuracy and repeatability of a computer-generated Pelli–Robson test.	LCD Pelli-Robson chart did not produce accurate results.

2.3 SMARTPHONE APPS FOR THE ASSESSMENT OF VISUAL ACUITY

The most well-known test, often regarded as a pertinent indicator of visual function is the Visual acuity test. (Brady et al., 2015). Both patients and physicians in all spheres of health care are generally familiar with the concept of "20/20" vision. VA can be assessed quickly and inexpensively with charts that are available commercially, online for printing and recently with smart devices (Brady et al., 2015). There are numerous VA apps available today on the Google play and Apple app store ready to be downloaded in seconds.

The most common VA charts available on these apps are the Snellen (letter and tumbling E optotypes) and the Sloan design VA chart. The apps provide an explanation to the user of what the test is assessing for and how to perform the test, but to an extent. The apps also generally inform the user of the specified distance the device should be held for optimum testing, however, apps such as the Variable Contrast Sensitivity test® and the Kay iSight Pro® test only provide information about the correct testing distance with no explanation as to what the app is testing for. After conducting the test, the app shows a result and recommends if the user should have a full eye examination or not.

The most widely researched VA app appears to be the "Peek acuity®" app. A few studies (Brady *et al.*, 2015; Rono *et al.*, 2015; Bastawrous *et al.*, 2015) have found the Peek acuity® app to be the most popular, as well as the most accurate and reliable when compared to VAs measured using the standard "5-letter-per-line" retro-illuminated logMAR charts. To the contrary, De Venecia *et al. (*2018) found that the "Peek acuity®" app

tended to overestimate the VA in scholars aged 6-16 years resulting in a false positive result and recommended that this app could be made more accurate if the sensitivity (found to be 48%) could be improved.

Smartphone VA app testing that proved to have accurate results was also noted with the "Paxos Checkup®" app (Pathipati *et al.*, 2016). This app was used to determine the VA of patients in a hospital emergency department (ED). During the first phase of the study the staff of the emergency department measured the patients' VAs using the standard 20 feet Snellen chart and in phase 2, measured patients near VAs using the "Paxos Checkup®" app. The test results from both phases were compared to VAs taken by ophthalmologists using the Rosenbaum near chart, which was treated as the benchmark. It was concluded that the best corrected visual acuity (BCVA) with the app was more accurate than when measured with a standard Snellen chart (Pathipati *et al.*, 2016). O'Niell *et al.* (2016) also assessed the validity of a VA test using smart technology devices in a primary care setting. 60 participants distance VA was assessed with a Snellen wall chart and on two smart- tech devices (iPhone and iPad). The results of both mobile apps compared very closely to the standard Snellen chart. The study (O'Niell *et al.*, 2016) postulated that this new type of testing method can result in more frequent VA testing and hence, potentially identifying ocular or other pathology at an earlier stage resulting in timely, referrals. Similarly, Han *et al.* (2019) also assessed distance and near VA using another mobile app, the V@home® mobile app, the results compared to that achieved with the standard (ETDRS) chart, as there were minimal discrepancies between the VA measurements across all groups (0.010 to −0.100 logMAR). The study concluded this new app was able to accurately and reliably assess both distance and near VA. Furthermore, using a survey the participants were asked about their views of the V@home® Smartphone testing app, with 82.3 % reporting that they were satisfied or extremely satisfied, in addition to 72.5% indicating that they were in favour of repeated use of the system again. This indicates that users of these apps are fairly receptive to trying new methods for assessing their vision.

While promising results were reported by the aforementioned studies, Pereira *et al*. (2015), Tofigh *et al.* (2015) and Zeri *et al.* (2018) found other smartphone VA tests to be unreliable or inaccurate. All three studies were conducted on different smartphone apps. Pereira *et al*. (2015) evaluated the results obtained with a smartphone-based VA chart (Dr. Bloggs Ltd® running on an Apple iPhone 4) against that obtained with a Snellen 6m VA chart at a university teaching hospital in Melbourne, Australia. A two Snellen line mean difference was noted between charts (0.276 logMAR). Those patients that had a VA poorer than 6/18 a larger mean difference in results was noted. Another VA app (Eye chart pro® app) only showed reliable results when the patients VA was better than 6/60. This study by Zhang *et al*. (2013) also tested the accuracy of a mobile app (Eye Chart Pro®) that was used on an iPad for testing VA. A total of one hundred and twenty participants underwent VA testing with the Eye Chart Pro app and these findings were compared against the conventional light-box chart. The results found by the iPad were greatly better than that of the standard chart ($p < 0.001$) (Zhang *et al*.,

2013). Similarly, Rhiu *et al*. (2016) found that when distance VA was assessed using an iPad, the logMAR VA was undoubtedly better than the iPad Tumbling E chart ($p < 0.01$) or iPad Landolt C chart ($p < 0.01$). It appears therefore that the apps may not be able to reliably determine reduced distance VA in users who actually have significantly reduced distance VA i.e. poor sensitivity.

Smartphone apps also exist for the assessment of near VA. Near VA measurement using the "Eye handbook®" iPhone app was compared to the conventional method of using a standard near VA chart (Tofigh *et al*., 2015). The study concluded that the "Eye hand Book®" tend to overestimates the near VA by 0.11 LogMAR compared to the standard near VA. The reason provided for this discrepancy was that the Apple iPhone 5 (1151:1) had a higher contrast ratio than the near card (33:1). The study further recommended that even though there has been an increase in the use of high-definition screens health care professionals need to be aware of the differences in VA results between the different types of testing methods.

Livingstone *et al*. (2016) postulated that optotype contrast and test luminance of devices could result in variation in VA measurements. This could affect the VA measurements and therefore any devices measuring VA for clinical purposes should have standardised charts and calibrations as standard test charts do. It has been recommended that chart luminance be 80 cd/m^2 or 120 cd/m^2, depending on the standard chart used (Livingstone *et al*., 2016). Moreover, Tofigh *et al*. (2015) asserted that the contrast ratio of a printed Snellen or ETDRS VA chart is below 33:1, whereas an iPhone screen has a higher contrast ratio of 1151:1. Therefore, he postulated that the possible mechanism causing a difference between results of the ETDRS VA chart and the Smartphone app was the higher contrast ratio of the iPhone vs the standard near chart. The study suggested that similar findings may also occur between other smart-tech platforms as well as standard test charts. It is therefore necessary to ensure that future smart-tech devices developed have comparable contrast and luminance to standard testing charts, as variations in these measurements can lead to possible discrepancies in VA results if standard testing charts are considered the gold standard for these measurements.

2.4 SMART TECHNOLOGY (IPAD) FOR THE ASSESSMENT OF CONTRAST SENSITIVITY

Measurements of CS better characterise visual performance than high contrast VA alone and subsequently can be used efficiently to detect visual compromise in conditions such as diabetes, glaucoma and AMD (Di Leo *et al*., 1992; Keane *et al*., 2010). Despite its potential benefits, CS testing in a clinical setting is infrequently performed due to long chair time and expensive equipment required. Smartphone app technology has however, ventured into this area. While there have been a few studies (Kollbaum *et al*., 2014; Zeri *et al*., 2018; Dorr *et al*., 2013; Rodriguez *et al*., 2014; Kingsnorth *et al.*, 2016) in the last decade that have conducted CS testing on other smart technology devices such as on an iPad and LCD computers, only one study was found that investigated CS on a smartphone device (Habtamu *et al*., 2019). This study used the same methodology as the

Peek VA® testing to develop and validate a Smartphone Peek Contrast Sensitivity (PeekCS®) test. The PeekCS® app test was compared to the standard tumbling-E Pelli-Robson CS test (PRCS). The PeekCS® test showed strong repeatability which was comparable with the PRCS. A faster testing time of (44.6 seconds) was achieved by the PeekCS® (44.6 seconds) when compared to the PRCS (48.6 seconds). The study concluded this app produced rapid and repeatable results which compared closely to the PRCS test.

A study by Kollbaum *et al*. (2014) aimed at determining the accuracy of a PRCS using an iPad. The study found that the iPad test showed good repeatability when compared to the standard Pelli-Robson test, and therefore concluded that this testing option could be a faster and timely alternative to existing clinical testing methods. In contrast, inaccurate CS test results using smart technology, more specifically a liquid crystal display (LCD) Pelli-Robson chart (electronic version), was reported by Zeri *et al*. (2018). The LCD chart results were compared to that of a standard Pelli–Robson chart to assess the performance of a LCD test. Two consecutive repeated readings at 1 m and at 3 m were conducted. The results revealed that the CS measured with the LCD resulted in significantly better results than the printed Pelli-Robson at both distances ($p < 0.01$). The study suggested that clinicians should be aware that CS results with the Pelli–Robson computer-generated version is not interchangeable with that obtained with the printed version.

Researchers are trying to develop new and cost-efficient ways for CS testing as many consider contrast sensitivity function (CSF) as a superior indicator of visual function than high contrast VA and can better monitor the slow progress of eye blinding diseases (Dorr *et al*., 2013 and Rodriguez *et al*., 2014). The study by Dorr *et al. (*2013) developed and validated an iPad CS test which was found to be efficient and user-friendly. The results demonstrated that the iPad test proved reliable at estimating sensitivities at specific spatial frequencies however, no specific spatial frequency value was mentioned in the article. The authors did however, state that the maximum sensitivities, which were repeatedly <1%, were observed at low spatial frequencies. This test also consistently found differences in contrast due to different luminance levels and it was concluded that CS testing on an iPad was indifferent from that of standard specialised testing.

A similar study to that of Dorr *et al*. (2013) was conducted by Rodriguez *et al. (*2014) who also designed a new CSF test (ClinicCSF) to be used on an iPad. Two versions of the ClinicCSF® were tested i.e. v1 and v2. Agreement was found between the functional acuity contrast test (FACT) and ClinicCSF® version2 for all spatial frequencies.

Kingsnorth *et al*. (2016) aimed to validate the accuracy and repeatability of a near and distance mobile app, the Aston contrast sensitivity test®. This study determined that smartphone apps found better CS than printed tests ($p = 0.005$). Furthermore, the Aston® near and distance apps proved to be valid, repeatable and a time-efficient method of assessing CS at multiple spatial frequencies. Moreover, Kingsnorth *et al. (*2016) asserted

that paper-based charts are often limited in the number of stimuli they can present and require the examiner to manually implement and respond to feedback from the patient. Hence, CSF can only be tested in broad discrete steps of spatial frequencies and contrast. Whereas, computer generated CSF testing cannot test multiple stimuli of various frequencies and contrasts making their use multifunctional and less time-consuming.

The most distinguishable observation between an iPad/ LCD computer and an iPhone, is the device size which plays a crucial role in how an app is presented on the intended screen. The screen of an iPad is much longer and wider when compared to that of an iPhone. The iPhone 6 plus has a 16:9 aspect ratio whereas the iPad has a 4:3 aspect ratio. A larger screen size usually results in a higher resolution which makes it difficult to resize some apps. The combination of the resolution and the aspect ratio means that running iPhone apps on the iPad can result in a stretched-out display or a black border surrounding the app display (Stone., 2019). This means that not all iPhone apps can be run on an iPad and vice versa, as this will result in inaccurate results due to the screen sizes and resolution being incorrect. In reference to the assertion by Livingstone *et al*. (2016) the discrepancies in contrast ratio, optotype, contrast and test luminance of devices can be possible reasons for the variation in CS measurements when using a smartphone device compared to standard clinical tests and the results obtained by the CS studies on an iPad or LCD device cannot apply to smartphone apps. Cox *et al*. (1999) also proposed another reason for the difference in contrast values between a standard printed chart and a smart device being the luminance of surrounding light. The authors (Cox *et al*., 1999) thus asserted that practitioners utilising standard letter CS charts do not need to make any further efforts to illuminate the standard test surrounding. However, practitioners measuring CS using computerized sinewave gratings, may have their measurements affected by inadequately lit surrounding light.

2.5 FACTORS FOR CONSIDERATION

Within each aspect of vision function screened for, there has been variability among the different apps such as optotype size, contrast and testing distance. A list of testing variability between the different apps are outlined below:

i. The brightness and contrast of smartphone screens differ making it difficult to compare the results produced by different apps (Khanna, 2017).
ii. The size and design of the optotypes used are different between apps, as well as in comparison to standard clinical tests.
iii. Smartphone optometric tests usually are not dimensionally the same as standard clinical tests, so the accuracy of the test results may differ if proper calibration is not implemented.

iv. Different smartphones have different screen sizes. All tests should be calibrated to the size of the smartphone screen and if this is not possible then the app should specify which smartphone is compatible with the app.

v. The instructions provided by the app are not always easy to understand hence, impacting the correct usage of the app and interpretation of results produced.

Thus, as is noted from previous studies, it is critical to assess smartphone devices to ensure the testing apps optotype size, luminance and optotype contrast are dimensionally correct and the test results are equally comparable to conventional tests as studies have shown that electronic versions of vision testing charts may not always produce the same results as standard tests do.

2.6 CONCLUSION

Studies show that the uptake and usage of Smartphones is unprecedented. There are numerous smartphone apps available on the iStore and Google play store, however, considering the literature that was studied, there are very limited studies on the accuracy of these smartphone apps, hence, questioning the accuracy and reliability of these apps and resulting in the reluctance of eye care professionals to use these apps in a clinical setting. These findings of this study will, therefore, help guide the usage of these smartphone screening apps by individuals as well as optometrists. Furthermore, the findings of this assessment can be useful in guiding the future development of these apps so that their use can be optimized for the delivery of a component of eye care, and subsequently health management.

CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

This chapter highlights the methodology utilised in answering the null hypothesis of this study. The study setting, population and sampling is described initially, followed by a detailed description of the data collection instruments and procedures. Information on how issues on validity and reliability of the method employed were ensured are provided. Thereafter, details on how the data was managed and analyzed is described. The chapter concludes with a summary of the ethical considerations for this study.

3.2 STUDY SETTING

This study was conducted at a private optometry practice (Spec-Savers) in the St. Georges Mall (Western cape), South Africa, during the period of August 2018 to May 2020.

3.3 STUDY DESIGN

This study was performed in two phases. Phase one employed a cross-sectional, comparative research design to compare the results of selected smartphone vision screening apps to their equivalent standard optometric test. Phase two utilised a quantitative, descriptive research design to determine the subjects' perceptions of the use of smartphone vision testing apps using a structured questionnaire.

3.4 STUDY POPULATION

The study population comprised of all patients between the ages of 18 to 55 years consulting at the Spec-Savers St George's Mall practice, during the period of August 2018 to July 2019. The demographic profile of the patients seen at the practice included the African, Caucasian, Indian and Mixed-Race groups. The majority of patients are of medium socio-economic standing and their occupations centered mostly in the business/computer field.

3.5 STUDY SAMPLE

Convenience sampling was used to select 100 subjects who satisfied the criteria outlined in Table 3.1. The sample size was determined using the G-power calculation which indicated a required sample size of 100 to achieve a 90% power with significance level of 0.05 to detect a minimum difference of 0.17 LogMAR.

Table 3.1: The inclusion and exclusion criteria of the study

Inclusion criteria	***Exclusion criteria***
Ages 18 to 35 years	Subjects not willing to sign consent form
Both genders	Unfamiliar with the English language
All race groups	
Any refractive error	

3.6 DATA COLLECTION INSTRUMENTS

3.6.1 A standard six meter Snellen VA chart was used to determine the participants' VA at distance. The Snellen chart uses the Snellen notation to display the VA results. The Snellen VA chart was chosen as this chart is the most widely available chart and allows easier display on projector systems. The VA measurements were taken monocularly and the eye that was measured first was randomised for the participants. The results were thereafter captured onto the data recording sheet in 6m Snellen notation for easy comparison.

3.6.2 The Pelli-Robson chart was used to determine the participants' CS at distance. The Pelli Robson chart is the most widely used chart to test CS. The Pelli-Robson chart is a wall mounted chart and is viewed from a distance of one meter. The chart uses ten Sloan letters with constant size. The chart consists of capital letters arranged horizontally which decrease in contrast with each subsequent line. The results were recorded in log contrast sensitivity (LogCS) and then converted into percentage notation using the Table 3.2.

Table 3.2: Conversion from Log CS to Contrast percentage (The Mars Perceptrix, 2003-2010).

log CS	Contrast	log CS	Contrast	log CS	Contrast	log CS	Contrast	log CS	Contrast	log CS	Contrast
0.04	0.912	0.08	0.832	0.12	0.759	0.16	0.692	0.20	0.631	0.24	0.575
0.28	0.525	0.32	0.479	0.36	0.437	0.40	0.398	0.44	0.363	0.48	0.331
0.52	0.302	0.56	0.275	0.60	0.251	0.64	0.229	0.68	0.209	0.72	0.191
0.76	0.174	0.80	0.158	0.84	0.145	0.88	0.132	0.92	0.120	0.96	0.110
1.00	0.100	1.04	0.091	1.08	0.083	1.12	0.076	1.16	0.069	1.20	0.063
1.24	0.058	1.28	0.052	1.32	0.048	1.36	0.044	1.40	0.040	1.44	0.036
1.48	0.033	1.52	0.030	1.56	0.028	1.60	0.025	1.64	0.023	1.68	0.021
1.72	0.019	1.76	0.017	1.80	0.016	1.84	0.014	1.88	0.013	1.92	0.012

3.6.3 A phoropter was used to perform a comprehensive refraction on each participant. The battery of tests for refraction comprised of retinoscopy, best sphere, duochrome test, Jackson cross-cylinder, as well as the Humphriss immediate contrast (HIC) test. These results were used to determine if the participant had some degree of confirmed astigmatism (≥ 0.50 DC).

3.6.4 An Apple (64 GB), iPhone 6 plus using IOS 9 was used as the smartphone device wherein all apps were downloaded. All apps were projected from this device on full brightness level and the necessary calibrations taken into consideration. The screen luminance of the iPhone 6 plus is approximately 150 cd/m^2.

3.6.5 A measuring tape was used to ensure the cellphone was placed at the appropriate distance specified by each app test which ensured that the test distance for each test was constant for all participants. Measurements of the test distance were taken with the tape measure starting at the outer canthus of the participant's eye and ending at the cellphone screen. This also ensured accuracy of results in this study.

3.6.6 Six different smartphone apps were chosen i.e. two apps each for VA, CS and astigmatism testing. For each parameter, one app was downloadable for free while the other required payment before it could be downloaded. The six apps are described below.

a. *Pocket Eye Exam*® (Visual acuity – free app)*:* This app was selected as it is free to download off the Apple app store for testing distance VA and the chart design used was a Snellen chart. The app provides instructions about the correct testing distance (6 ft) that the phone should be held at but no information was given as to what the app is testing for. The VA test results are displayed in 20/20 Snellen notation which was thereafter converted by the researcher into 6m Snellen notation for easy comparison between the different apps and the standard test.

b. *Smart Optometry*® (Contrast sensitivity – free app)*:* The chart used on this app is a Pelli-Robson test design consisting of eight rows of letters and six capital letters per line. The app provides instructions on how to perform the test, as well as explanations of what the test is testing for and the correct testing distance the phone should be held. The test results are displayed in an easy to understand percentage notation. These results were thereafter converted into LogCS for easy comparison to the standard Pelli-Robson test.

c. *Eye Meter*® (Astigmatism – free app): This app employs a fan chart astigmatism wheel. The chart has a white background with a dark blue astigmatism wheel. The app provides instructions on how to perform the test, as well as explanations of what the test is testing for and the correct testing distance the phone should be held. The test results are displayed in an easy to understand 'Pass/ Fail' criteria and a referral as to whether you should have an eye examination is suggested.

d. Kay iSight Professional® (Visual acuity – paid app): This app was purchased from the Apple app store for R 69.99. This app tests both distance and near VA using Kay letters. The results can be displayed in LogMAR, Snellen and decimal notation. Only testing distance information was given by this app.

e. *Variable Contrast Sensitivity test*® (Contrast sensitivity – paid app): This app was purchased for R 199.99 from the Apple app store. This app tests both distance (2m and 3m) and near (40cm) CS. This app tests CS from 1.25% to 100%. The chart used was a Pelli-Robson chart design presenting five letters of high contrast first and then decreasing in contrast with each subsequent row of letters. The results are displayed in an easy to understand a percentage notation which was thereafter converted into LogCS. The app does not give instructions on how to perform the test or what the test is testing for.

f. Eye *test*® (Astigmatism – paid app): This iPhone optometric app costs R 14.99 to purchase off the Apple app store. This test contains a high contrast black astigmatism fan and block astigmatism wheel against a white background. This app provides clear test instructions, as well as correct testing distance the Smartphone should be held. The results are displayed is an easy to understand 'Pass/ Fail' criteria.

The results from all of the above app tests, as well as the standard tests were recorded onto the data recording sheet (Appendix 1). The data recording sheet was used to capture each participant's test results. The table was in a 3x4 format. There were three separate tables, each table displayed the results of a single optometric test namely, VA, CS or astigmatism.

For the VA table, the dependent variable consisted of the three types of VA tests used, namely, a Snellen 6-meter VA chart, Free App: *Pocket Eye exam*® and the Paid App: *Kay iSight Professional*®. The independent variables were the results of the right and left eyes.

For the CS table, the dependent variable consisted of the three CS tests used viz. The standard Pelli-Robson test, Free app: *Smart Optometry*® and the Paid app: *Variable Contrast Sensitivity*® test. The independent variables were the results of the right and left eyes.

For the Astigmatism table: The tables dependent variable was the three astigmatism tests performed that will include the standard JCC test, the Free app: *Eye Meter*® and the Paid app: *Eye test*®. The independent variables were the results of the right and left eye.

3.6.7 A structured questionnaire (Appendix 2) was used to collect information about the participants. There were three main sections in the questionnaire. Section One captured the demographic profile of the participants including age, gender, race and occupation. Section Two contained questions that compared the standard optometric test to the smartphone apps. Questions in Section Three were closed-ended questions relating to the three types of apps used (VA, CS and Astigmatism). The questions revolved around the ease of use of the apps, instructions by the apps as well as the participant's subjective opinion of each of the tests. The questionnaire was based on a previously published questionnaire in this field of research and was validated in the pilot study. The data from the pilot study was used in the main study. The questionnaire took approximately 5 minutes to complete 11 questions. It was available only in English.

3.7. DATA COLLECTION PROCEDURE

Data collection commenced once relevant ethical clearance had been obtained (BE703/18) (Appendix 4). The participants recruited for this research were patients coming in for eye tests at the Spec-Savers St. George's Mall optometric practice. Before they had begun their optometric examination, the principal researcher informed the respondent of the nature of the study and invited them to participate. If the participant was keen on being a part of the study, informed consent was obtained before proceeding with the research (Appendix 4).

3.7.1 Part A

Optometric testing commenced in the conventional sequence. Standard testing for VA, CS and astigmatism were completed first. After the full eye examination was completed, participants were presented with the six smartphone apps to assess VA, CS and astigmatism, the presentations of which were randomized. The results

were captured onto the data recording sheet. All tests were performed on both the right and left eyes. Room lighting and test distance was controlled and standardised for each test.

Standard optometric tests

a. Distance Visual Acuity

Distance VA was assessed using the projector Snellen VA chart. The projector screen was positioned four meters away from the participant, and the projector had been calibrated accordingly. The researcher first explained what a VA test was, thereafter, she explained to the participant that she would be testing their vision at distance. The participant was instructed to occlude their eye (the starting eye was randomized for the different participants) and thereafter they recited the letters on the chart back to the researcher starting from the 6/120 line. The participant was asked to read the first letter on each following line until an error was made, then read all letters across the line. The VA score was determined in the following way:

i. If the participant read the entire row of letters correctly and stopped there, the researcher recorded the VA as that line.
ii. If the participant read more than half the letters on a row correctly, the researcher recorded the VA as that line minus the number of letters the participant got incorrect.
iii. If the participant read less than half the number of letters on a row correctly, the researcher recorded the VA as the previous line plus the number of correctly identified letters on the last line read.

The best VA measurement was determined on one eye and thereafter, the exact same procedure was performed on the other eye to determine the VA. A pass was regarded as a VA score of 0.63 (equivalent to 6/9) or less. The pass value of 6/9 was chosen because this value is the minimum VA measurement that is required of any person to successfully pass their driver's screening test. The VA measurement was recorded in 6-meter Snellen notation.

b. Contrast Sensitivity

The Pelli-Robson test was conducted to assess the participant's CS at distance. This test was performed after the amplitude of accommodation was measured. The Pelli-Robson test chart was placed at a distance of one meter away from the participant. This test measures CS using a single large letter size (20/60 optotype). The chart has eight rows of six letters each. Each line consists of two triplets. Each triplet contains letters of equal contrast, and the contrast of each triplet decreases by a factor of 0.15 log units. The contrast varies from 100% (0.00 log units) to 0.56% (2.25log units). The participant was asked to read the letters, starting with the highest contrast, until they are unable to read two or three letters in a single group. The participant was assigned a

score (Log CS) based on the contrast of the last group in which two or three letters were correctly read. The score was recorded in Log CS and then converted into percentage notation (using Table 3.2). A pass was regarded as a contrast score of 1.65 or better (Aziz, 2014). Any value less than this was regarded as a fail. The final score was recorded on the data recording sheet. This procedure was performed on both the right and left eyes.

c. Determination of Astigmatism

The presence of astigmatism was assessed during the subjective refraction, in particular during the Jackson Cross-Cylinder (JCC) test. Once the best sphere was determined, the participant was asked to focus on a letter "O" and the axis of astigmatism (minus cylinder form) was determined using the recommended procedure when doing the JCC test. Once the axis was determined, the power of astigmatism was determined. An astigmatism value of -0.50D or higher, was regarded as being clinically significant and taken to indicate that the participant had astigmatism. The results were then captured onto the data recording sheet by the researcher. This procedure was performed on both the right and left eyes.

Smartphone app tests

a. Distance Visual Acuity

Distance VA was assessed using two apps viz. the Kay iSight Test Professional® and Pocket Eye Exam® apps. The participants were not given any instructions on how the test is performed or what each test was testing for. He/she had to read the instructions given by the app and perform the test accordingly. The only instruction that was given to the participant was that he/she must read the letters aloud and if the app has multiple chart designs, he/she was instructed to ONLY perform the Snellen VA test. The VA measurement for each eye was recorded on the data recoding sheet accordingly.

b. Contrast Sensitivity

The Smart Optometry® and Variable Contrast Sensitivity® apps were used to assess CS of the participant. As with the previous tests the participant was not given any verbal instructions from the researcher and he/she had to read and follow the instructions of the app. Once the participant had read and performed the test on each eye the researcher recorded the results in a percentage notation onto the data recording sheet.

c. Astigmatism

An assessment of the presence of astigmatism was determined using the Eye Meter® and Eye test® Smartphone apps. Here again, the participant was not given any instructions how the test was performed or what each test was testing. He/she had to read the instructions given by the app and perform the test

accordingly. The test was conducted on both the RE and LE. The astigmatism result was recorded on the data recording sheet.

3.7.2 Part B

After performing all standard optometric tests, as well as the smartphone optometric screening tests, the participants were asked to complete a questionnaire consisting of 11 questions with a multiple-choice design pertaining to both the standard tests, as well as the apps. All questions were closed-ended. There were three main sections to this questionnaire. Questions in Section One captured the demographic profile of the participants including age, gender, race and occupation. Section Two contained questions that compared the standard optometric tests to the smartphone app tests. The questions related to the participants' preferred testing procedure, which method had the easier testing instructions, as well as their preferred testing method for future. Questions in Section Three revolved around the usability, the ease of use, instructions by the apps, as well as the participant's subjective opinion of each of the three smartphone apps (VA, CS and astigmatism). The researcher was within proximity to attend to any queries that the participants could have had regarding the questionnaire.

3.8 PRODUCT OF RESEARCH

The findings of this study will be disseminated using publications in relevant peer-reviewed journals and conference presentations. Thus far two manuscripts (Appendices 7 and 8) have been submitted for consideration to the journals Ophthalmic Epidemiology and Indian Ophthalmology respectively

3.9 PILOT STUDY

A pilot study was conducted on ten participants who met the inclusion criteria. The pilot study results, and feedback was used to modify the proposed study procedure and questionnaire, if required, before commencement of data collection.

3.10 VALIDITY AND RELIABILITY

3.10.1 All standard optometric tests, included in the study, are established tests for determining VA, CS and astigmatism. Various studies (Boslaugh *et al*., 2018; Levy *et al*., 1974; Elliot *et al*., 1990; Priors *et al*., 1986 and Persson *et al*., 1973) have been used accordingly to assess the same aspects of vision.

3.10.2 All optometric tests conducted are within the scope of practice of the researcher.

3.10.3 All tests were conducted by the researcher ensuring standardisation of instructions, procedures and recording.

3.10.4 The same iPhone was used for all apps and on all participants.

3.10.5 The smartphone apps chosen are registered on the Apple app store.

3.10.6 Before the commencement of data collection a pilot study was conducted to validate the data collection instruments, procedures and recording.

3.10.7 All standard optometric tests were conducted as per published procedure in reference texts (Kolker., 2015).

3.10.8 All smartphone app testing was conducted according to the manufacturer's recommendations.

3.10.9 Both standard optometric tests and iPhone apps were conducted under normal lighting conditions (1300 lux)- wozniak et al. 1999.

3.10.10 The researcher was available to provide clarification, if required, during the completion of the questionnaire.

3.10.11 Each app optometric test was analysed to ensure that each test's optotype size is calibrated to be used at their specific distance.

3.10.12 To ensure reliability the questionnaire was piloted before the study. The questionnaire was self-administered; however, the researcher provided clarification if it was required.

3.11 DATA ANALYSIS

Statistical data analysis was conducted using the Statistical Package for Social Sciences (SPSS) v25 in conjunction with a statistician. Descriptive statistics including frequencies, means, medians and Inter Quartile Ranges were used to report the results. Because the data was not normally distributed, the Wilcoxon signed ranked test was used to compare two paired groups to essentially calculate the difference in means and to assess for statistically significant differences at a 95% confidence level ($p<0.05$). Cross-tabulations and the Chi-squared test were used to investigate any associations between categorical variables. The results are illustrated using tables and figures.

3.12 DATA MANAGEMENT

Data was captured by the researcher only. The electronic data will be stored in a password protected electronic device. The researcher will be the only person who will have access to this storage facility. The raw data will be retained for a 5 year period, following which it shall be shredded and discarded of accordingly.

3.13. ETHICAL CONSIDERATIONS AND CONFIDENTIALITY

This study adhered to the tenets of the Declaration of Helsinki.

3.13.1. Permission was obtained from the proprietor of St. Georges Mall Spec-Savers to conduct the research on their premises and use the available equipment (Appendix 5).

3.13.2. Ethical clearance was obtained from the Biomedical Research Ethics Committee of the University of KwaZulu-Natal prior to data collection (Appendix 4).

3.13.3. Informed consent was obtained from the participants.

3.13.4. The identity of the subject will remain anonymous.

3.13.5. Participant's personal information was kept confidential and they were only be identified by their participation number.

3.13.6. None of the tests were invasive and therefore posed no risk to the participant.

3.13.7. Password protected electronic devices were used to store the data.

3.13.8. Raw data will be archived in a secure cabinet**.**

3.14 CONCLUSION

Data was collected during the period of January 2019 to July 2019. A total of 113 participants were enrolled in the study. The pilot study was effective in modifying the data collection procedure, as well as the data collection tool. With the help of a statistician and SPSS the data was skillfully analysed. The study utilised convenience sampling which thus involved the use of a sample of the population which was close at hand. Standardised procedures and settings were utilised during the data collection. The analysis of the data collected will be presented in Chapter Four.

CHAPTER FOUR

RESULTS

4.1 INTRODUCTION

This chapter is a concise presentation of the research findings. The results are presented by means of figures, graphs and tables. Comparisons of the results from the standard and smartphone tests were made to determine if these app tests provide accurate and reliable results. The responses from the participants are also analysed in this section to determine the users' perspectives on smartphone testing compared to standard clinical testing.

4.2 DEMOGRAPHICS

There was a total of 113 participants in this study, however as one participant was monocular, results were obtained for 113 right eyes but only 112 left eyes. Almost two-thirds of the participants were female (61.1%, n = 69) and the majority of the participants were Black African (Figure 4.1). The ages of the participants ranged from 18 to 35 years with a mean age of 27.56 ± 4.30 years. The median age was 27 years.

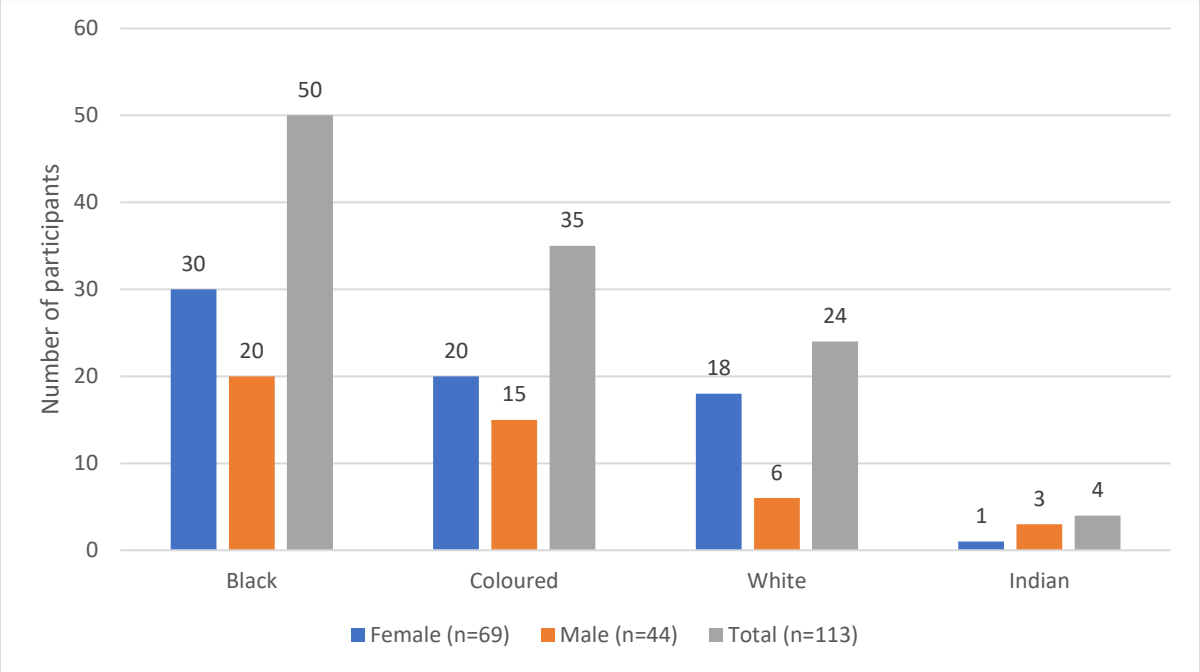

Figure 4.1: Number of participants according to race and gender

The participants' occupations were classified into three main categories according to their frequency of computer use and included minimal computer use, moderate computer use, and high computer use. The high computer use category included office workers (16.8%), call centre agents (12.4%) and students (11.5%). More than half of the participants (53.1%) fell in the high computer use category. Moderate computer use

(24.8%) included social workers (0.9%), sales representatives (3.5%) and fashion designers (0.9%); and then minimal computer users (22.1%) included actor/model (1.8%), cleaners (1.8%) and truck drivers (1.8%). The stratification of these categories according to gender is shown in Table 4.1.

Table 4.1: Frequency of computer use according to gender

	Female	**Male**	**Total**
	n (%)	**n (%)**	
Minimal computer usage	14 (20.3%)	11 (25.0%)	25 (22.1%)
Moderate computer usage	20 (29.0%)	8 (18.2%)	28 (24.8%)
High computer usage	35 (50.7%)	25 (56.8%)	60 (53.1%)
Total	**69 (61.1%)**	**44 (38.9%)**	**113 (100%)**

4.3 REFRACTIVE STATUS

The majority of the participants in this study had low myopia (spherical component <3 Diopters) in the RE and LE and low astigmatism (cylindrical component < 1D) (Griffin Eye Centre, 2020) (Table 4.2). There were only 10 participants (8.85%) that presented with either low (<3D) (RE: 7% and LE: 8%) or moderate (<6D) (RE: 1% And LE: 2%) hyperopia. There was a total of four emmetropes in this study.

Table 4.2: Classification of refractive status for the right and left eye of participants.

	Myopia		Hyperopia		Astigmatism	
	Right eye	Left eye	Right eye	Left eye	Right eye	Left eye
Low	53	58	7	8	49	57
Moderate	9	7	1	2	20	19
High	2	2	0	0	0	0
V.High	0	0	N/A	N/A	N/A	N/A
Total	**64**	**67**	**8**	**10**	**69**	**76**

4.4 DISTANCE VISUAL ACUITY

The accuracy of the Pocket Eye Exam® (in this section referred to as the Free App) and the Kay iSight Test Professional® iPhone app (in this section referred to as the Paid App), for measuring distance VA (DVA) was assessed by comparing the results obtained with the apps to that produced by standard optometric distance vision measurement with a Snellen chart.

4.4.1 *Median Distance Visual Acuity*

A total of 225 distance VA measurements from 113 participants were obtained using the standard 6m Snellen VA chart, as well as on the free and paid smartphone apps. The results of the right eyes (n = 113) are separated from that of the left eyes (n = 112). All measurements were converted into decimal notation for comparison (Table 4.3). As the data was not normally distributed, the medians and not the means are presented.

Table 4.3: Median DVA with interquartile range (IQR) in decimal notation obtained with the Snellen chart, free App (Pocket Eye Exam®) and paid App (Kay iSight Test Professional®)

	RIGHT EYES	LEFT EYES
	Median (IQR)	**Median (IQR)**
Snellen Chart	0.63 (0.20; 1.00)	0.63 (0.20; 1.00)
Free App	0.63 (0.25; 1.00)	0.63 (0.32; 1.00)
Paid App	0.63 (0.20; 1.00)	0.63 (0.25; 1.00)

The median for both VA apps and the Snellen test were exactly the same (0.63) for both the right and left eyes. Even though the median was consistently 0.63 for all tests, the lower IQR for the free app (RE and LE) and paid app (LE) scores were slightly higher than the lower IQR for the Snellen test.

As the data was not normally distributed the Wilcoxon signed ranked test was used to test for statistical significance. When comparing the DVAs of the right eyes obtained with either apps to that of the Snellen chart, the differences were statistically significant (p values <0.01). Similarly, statistically significant differences were also obtained for the left eyes when comparing the standard test to the Free and Paid apps. However, when the difference in IQR between the right eye measurements obtained with the Snellen chart compared to the Free and Paid app values, the IQR difference was always less than 0.1 decimal notation which would have indicated not more than a one-line difference in DVA. This was the same for the left eyes as well. This indicates no clinically significant differences in DVAs between the standard test and either apps.

Females showed a constant median of 0.63 for the standard test, as well as the two smartphone tests except for the median for the left eyes with the Paid app which was slightly higher (1.00). Males also had a constant left eye median of 0.63 for the standard test and the Free and Paid apps, whereas the VAs for the right eye with both the Paid and Free apps tended to have a higher median than the standard Snellen VA. Males had a lower median than females in the right eye for the standard test whereas both genders had the same median in the left eye. Females tended to have a higher median in the left eye than males for the Paid app and males showed a lower right eye median than females for the Free app. However, the median and IQR differences between both genders for the right and left eyes for all three test formats were always <0.1 indicating not even a 1-line difference in Snellen VA, which overall is not clinically significant.

Table 4.4: Showing the Median and IQR for distance VA in decimal notation according to gender.

	Median (IQR)			
	Female		**Male**	
	RE	LE	RE	LE
Snellen chart	0.63(0.20;1.00)	0.63(0.20;1.00)	0.50(0.18;0.80)	0.63(0.20;1.00)
Paid app	0.63(0.32;1.00)	1.00(0.32; 1.00)	0.63(0.24;1.00)	0.63(0.29;1.00)
Free app	0.63(0.20;1.00)	0.63(0.25;1.00)	0.57(0.20;0.80)	0.63(0.21;1.00

4.4.2 *Pass/Fail categorisation of Distance Visual Acuity*

Measurements for distance VA for all three tests were further categorised into pass and fail (Table 4.5). A pass was regarded as a VA score of 0.63 (equivalent to 6/9) or less. This passing criteria value of 6/9 was selected because the minimum vision requirement for driving on South African roads is 6/9 hence, this is one of the most common tasks that most people will need to engage in and often would use vision screeners to assess their VA.

Table 4.5: Showing the frequency of pass and fail categorisation of distance visual acuity obtained with the Snellen chart, Free and Paid Apps.

	RIGHT EYES		LEFT EYES	
	PASS (n) (%)	**FAIL (n) (%)**	**PASS (n) (%)**	**FAIL (n) (%)**
Snellen Chart	58 (51.3%)	55 (48.7%)	67 (59.3%)	45 (39.8%)
Free App	69 (61.1%)	44 (38.9%)	70 (61.9%)	42 (37.2%)
Paid App	63 (55.8%)	50 (44.2%)	67 (59.3%)	45 (39.8%)

A higher percentage of participants, when considering both right and left eyes, were able to pass the distance VA test with the Free app when compared to the Snellen chart and the Paid app, resulting in a relatively higher overestimation rate by the Free app. The Paid app also tended to overestimate the distance VA when compared to the Snellen chart however, the overestimation was not as high as with the Free app.

4.4.3 *Sensitivity and specificity of visual acuity tests*

Sensitivity refers to the ability of a test to correctly identify those individuals that have a disease, while specificity is the ability of a test to correctly identify those individuals who do not have the disease. In this context, "disease" was taken to be distance visual acuity of less than 6/9 (0.63). The specificity and sensitivity was calculated using the z-test and the exact binomial distribution.

Table 4.6: Showing the Sensitivity and Specificity of the Free App for Distance Visual Acuity for the right and left eyes in relation to the Snellen chart

	Snellen VA (Gold Std)			
	True Pass		**True Fail**	
	RE	**LE**	**RE**	**LE**
Free App - Pass	42	39	2	3
Fail App – Fail	13	6	56	64
Total	55	45	58	67
	Sensitivity		Specificity	
	76	87%	97%	96%

The Free App showed higher sensitivity for the left eyes compared to the right eyes, while the specificity of the right and left eyes was found to be almost the same (Table 4.6). Slightly higher values of sensitivity and specificity were found for the Paid App for the right and left eye (Table 4.7).

Table 4.7: Showing the Sensitivity and Specificity of the Paid App for Distance Visual Acuity for the right and left eyes in relation to the Snellen chart.

	Snellen VA (Gold Std)			
	True Pass		**True Fail**	
	RE	**LE**	**RE**	**LE**
Paid App - Pass	49	43	1	2
Paid App – Fail	6	2	57	65
Total	55	45	58	67
	Sensitivity		Specificity	
	89%	96%	98%	97%

4.5 CONTRAST SENSITIVITY

The results produced by Smart optometry® (in this section referred to as the Free App) and Variable Contrast sensitivity® (in this section referred to as the Paid App) iPhone apps for the assessment of CS was compared with the clinical measurements obtained with the standard Pelli-Robson chart. As the results were not provided in the same notation for each of the three different tests, the comparison for CS is done in terms of the "Pass/Fail" criteria.

4.5.1 Pass*/Fail Categorization of contrast sensitivity*

A pass was regarded as a contrast score of 1.65 and better (Aziz, 2014). Any value less than this was regarded as a fail. More participants, for both the right and left eyes, passed the CS test with the Free and Paid app as compared to the standard Pelli-Robson test (Table 4.8). When the apps were compared to each other, more participants passed with the Paid app than the Free app. Logistic regression analysis found there to be statistically significant differences. The Free app compared more closely to the standard Pelli- Robson ($p<0.001$) test result than the paid app ($p=0.345$) which tended to overestimate the CS results for both the right and left eye when compared to the Pelli-Robson test results. All three tests, for both the right and left eyes, produced statistically significantly different CS ratings (p values <0.01) when compared to each other.

Table 4.8: Showing percentage of pass and fail categorisation of contrast sensitivity determined with the Pelli-Robson chart, free and paid app.

	RIGHT EYES		LEFT EYES	
	PASS (%)	**FAIL (%)**	**PASS (%)**	**FAIL (%)**
Pelli-Robson chart	(61.9%)	(38.1%)	(59.3%)	(39.8%)
Free App	(69.0%)	(30.1%)	(68.1%)	(31.0%)
Paid App	(85.8%)	(14.2%)	(83.2%)	(15.9%)

When stratified according to gender the same trend of the free app results comparing more closely to the Pelli-Robson chart results were noted for both females and males. A much larger percentage of males (90.9%) passed the CS testing with the Paid app than females that passed with that app (82.6%) for the right eyes, with similar findings for the left eyes (Table 4.9).

Table 4.9: Showing the percentage of pass and fail categorisation for contrast sensitivity determined with the Pelli-Robson chart, Free and Paid app according to gender.

	PASS (%)				FAIL (%)			
	Female		Male		Female		Male	
	RE	LE	RE	LE	RE	LE	RE	LE
Pelli - Robson	60.9%	59.4%	63.6%	59.1%	39.1%	40.6%	36.4%	38.6%
Paid app	69.6%	66.7%	70.5%	70.5%	30.4%	33.3%	29.5%	27.3%
Free app	82.6%	79.7%	90.9%	88.6%	17.4%	20.3%	9.1%	9.1%

When comparing the contrast sensitivity results of the Pelli-Robson chart to the free app for both males and females, similar trends were noted for both the right and left eyes where the Free app was found to pass more participants than the standard test.

4.5.2 *Sensitivity and specificity of the contrast sensitivity tests*

The Free app showed much higher specificity than sensitivity when screening for CS, in relation to the Pelli-Robson chart, for both the RE and LE (Table 4.10).

Table 4.10: Showing sensitivity and specificity of the Free App for CS for the RE and LE in relation to the Pelli-Robson chart

	Pelli-Robson (Gold Std)			
	True Pass		**True Fail**	
	RE	**LE**	**RE**	**LE**
Free App - Pass	68	66	11	11
Free App – Fail	2	1	32	34
Total	70	67	43	45
	Sensitivity		Specificity	
	74%	76%	97%	99%

The sensitivity of the Paid app for both the right and left eyes (Table 4.11), in relation to the Pelli-Robson chart was much lower than its specificity as well as, lower than the sensitivity of the Free app (Table 4.10). However, the Paid app had very high specificity values for both the RE and LE.

Table 4.11: Showing sensitivity and specificity of the Paid app for CS for the RE and LE in relation to the Pelli-Robson chart.

	Pelli-Robson (Gold Std)			
	True Pass		**True Fail**	
	RE	**LE**	**RE**	**LE**
Paid App - Pass	69	65	28	29
Paid App – Fail	1	2	15	16
Total	70	67	43	45
	Sensitivity		Specificity	
	35%	36%	99%	97%

4.6 ASTIGMATISM

4.6.1 *Detection of astigmatism*

The results obtained for the assessment of astigmatism by the Eye test® (in this section referred to as the Paid App) and Eye Meter® iPhone app (in this section referred to as the Free App) were compared to the JCC values after a subjective refraction was performed.

More than half of the participants had at least 0.50D of astigmatism in the RE (59.3%) and LE (61.1%) as determined with the standard JCC test. Statistically significant ($p<0.001$) lower percentages of participants, as determined by the chi squared test were detected as having astigmatism by both the Free and the Paid apps (Table 4.12).

Table 4.12: Showing the frequency of participants with astigmatism and no astigmatism as determined with the JCC test, Free and Paid apps.

	RIGHT EYES		LEFT EYES	
	No Astigmatism (%)	**Astigmatism (%)**	**No Astigmatism (%)**	**Astigmatism (%)**
JCC test	46 (40.7%)	67 (59.3%)	43 (38.1%)	69 (61.1%)
Free App	83 (73.5%)	30 (26.5%)	84 (74.3%)	28 (24.8%)
Paid App	65 (57.5%)	48 (42.5%)	68 (60.2%)	44 (38.9%)

While both the Free and the Paid apps underestimated the number of participants having astigmatism when compared to the JCC test, for both the right and left eyes, the Free App appeared to miss more of the astigmatism than the Paid App.

When the results were further stratified according to gender, similar results were noted. In comparison to the JCC test, both apps underestimated the number of females and males that presented with astigmatism (Table 4.13). Again, the results provided by the Paid App was a little closer to that of the JCC test in both genders, compared to the Free App.

Table 4.13: Showing the frequency of participants with astigmatism and no astigmatism as determined with the JCC test, Free App and Paid App classified according to gender

	No Astigmatism (%)				Astigmatism (%)			
	Female		Male		Female		Male	
	RE	LE	RE	LE	RE	LE	RE	LE
JCC test	30 (43.5%)	30 (43.5%)	16 (36.4%)	13 (29.5%)	39 (56.5%)	39 (56.5%)	28 (63.6%)	30 (68.2%)
Paid app	53 (76.8%)	52 (75.4%)	30 (68.2%)	32 (72.7%)	16 (23.2%)	17 (24.6%)	14 (31.8%)	11 (25.0%)
Free app	44 (63.8%)	44 (63.8%)	21 (47.7%)	24 (54.5%)	25 (36.2%)	25 (36.2%)	23 (52.3%)	19 (43.2%)

4.6.2 *Sensitivity and specificity for the detection of astigmatism*

The specificity of the Free App in the right eye was 45% and the sensitivity of the right eye was undefined due to the false positive value being 0. The left eye had an 88% sensitivity and the specificity was undefined. A 45% specificity of the right eye indicated this test was not good at identifying those participants with no astigmatism.

Table 4.14: Showing the sensitivity and specificity of the Free App for the identifying of astigmatism for the RE and LE in comparison to the JCC test

	JCC test			
	True Pass		**True Fail**	
	RE	**LE**	**RE**	**LE**
Free App - Pass	30	28	0	0
Free App – Fail	37	41	39	43
Total	67	69	39	43
	Sensitivity		Specificity	
	undefined	88%	45%	undefined

The sensitivity and specificity for the right eye was determined as 98% and 70%, respectively and the sensitivity of the left eye was 36% and the specificity was undefined (Table 4.15). The left eyes had very low sensitivity (36%) indicating this test is not adequate in identifying individuals with astigmatism.

Table 4.15: Showing the sensitivity and specificity of the Paid App for the identifying of astigmatism for the RE and LE in comparison to the JCC test

	JCC test			
	True Pass		**True Fail**	
	RE	**LE**	**RE**	**LE**
Paid App - Pass	45	25	20	43
Paid App – Fail	1	44	47	0
Total	46	69	67	43
	Sensitivity		Specificity	
	98%	36%	70%	Undefined

4.7 QUESTIONNAIRE

The questionnaire was used to determine the participants' views of smartphone app screening versus standard testing. All participants (N = 113) completed a questionnaire consisting of 11 questions after the standard and app testing was performed.

4.7.1 *Preference of testing format according to gender*

When participants were asked which testing procedure they preferred, 74.3% chose the standard testing method, 23.0% the smartphone app and 2.7% indicated no specific preference. The majority of males (75%) and females (74%) preferred the standard test. Approximately equal percentages of females (23.2%) and males (22.7%) choose the smartphone test. Of those that preferred the standard testing option (Figure 4.2), 40.7% chose this option because they felt it was more reliable, 27.4% because it was familiar to them, 16.8% found it to be more interactive and 9.7% chose this option because it was easier to understand. It was found that more males (47.7%) than females (36.2%) chose the standard test as being more reliable and more females (30.4%) than males (22.7%) chose familiarity as the reason for selecting the standard test as their preferred testing option

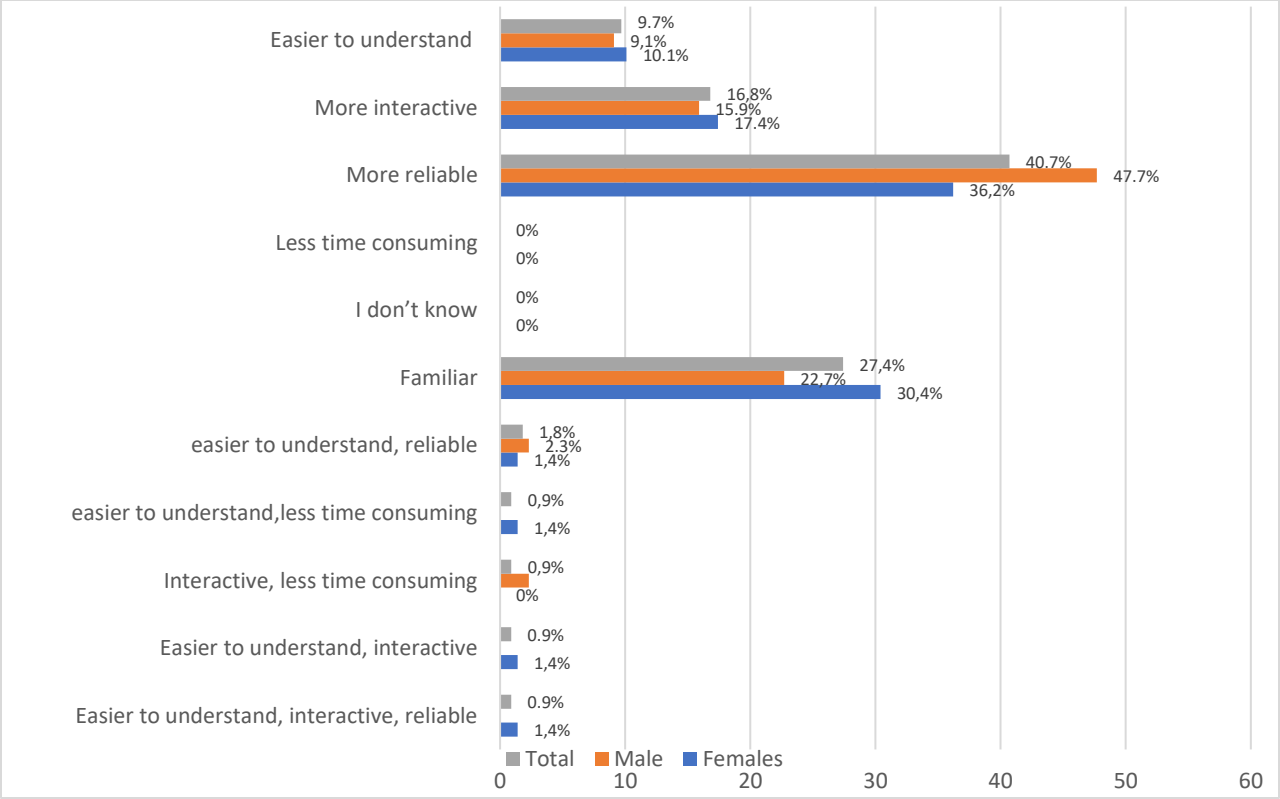

Figure 4.2: Showing reasons for selecting the standard test as preferred testing option stratified according to gender

Even though the majority of participants (74.3%) preferred the standard test, when asked which testing method had "easier to understand" instructions, 63.7% of participants said both the standard and app tests were equally easy to understand.

4.7.2 *Preference of testing format according to age*

Figure 4.3 shows that the majority of all age groups (85% of 30 to 35 year olds, 76% of 25 to 29 year olds and 59% of the 18 to 24 year olds) preferred the standard testing. It was further noted that of those that preferred the smartphone testing, the greatest proportion (34%) were from the youngest age group (18 to 24 year olds). It is clear from these findings that the older population would prefer the normal standard testing procedure and the younger age range would choose the smartphone testing.

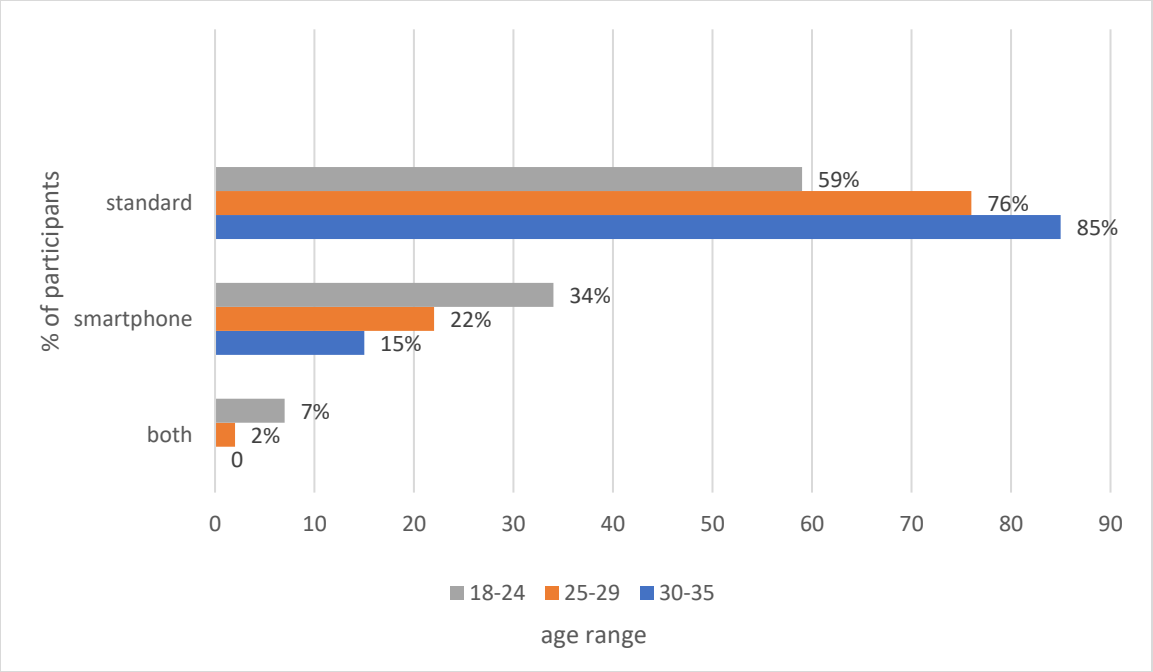

Figure 4.3: Distribution of preference according to age group

Figure 4.4 shows the age stratification for the different reasons chosen for preference of testing method. The most popular reason for preference of a particular testing method varied among the age groups. Familiarity with a test appeared more important to the older subjects (30-35 years), reliability of the test for the middle age group (25-29 years), and being interactive for the younger age group.

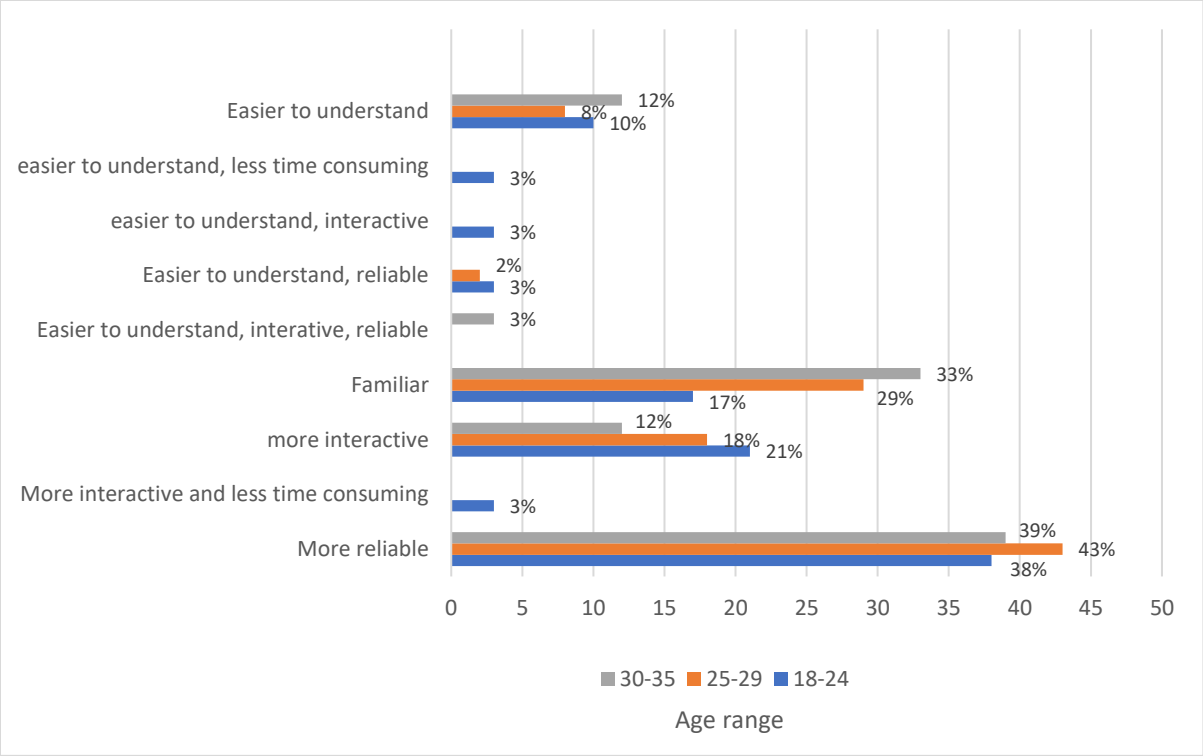

Figure 4.4: Reasons for testing format preference according to age groups

4.7.3 *Preference of testing format according to occupation*

Of the participants that fell into the "high computer use" occupational category, the majority (81.7%) chose the standard test as their preferred testing method, 16.7% chose the smartphone app and 1.7% chose both the standard and smartphone testing. This trend was also noted for the "moderate" and "minimal computer use" participants (Table 4.16). Using Fisher's exact test (p-value 0.002) it was determined that regardless of the frequency of use of a computer the majority of participants belonging to the minimal, moderate and high computer use occupational category choose the standard test as their preferred testing procedure. The same association was found when we compared the participants' preferences for their next eye examination to their occupational group. Fisher's exact test (p-value 0.017) found that frequency of computer use did not affect the participant's preferences as the majority of participants still chose the standard test to be used at their next eye exam.

Table 4.16: Occupational categories compared to Q1 and Q4

	Minimal	Moderate	High	Total	Statistical Test	p-value
Total	25	28	60	113		
Q1						
1. Standard	19 (76%)	16 (57.1%)	49 (81.7%)	84 (74.3%)	Fishers exact test	0.022
2. Smartphone	4 (16%)	12 (42.9%)	10 (16.7%)	26 (23.0%)		
3. Standard and Smartphone	2 (8.0%)	0 (0.00%)	1 (1.70%)	3 (2.70%)		
Q2						
1. Standard	21 (84%)	18 (64.3%)	53 (88.3%)	92 (81.4%)	Fishers exact test	0.017
2. Smartphone	3 (12.00%)	10 (35.7%)	7 (11.7%)	20 (17.7%)		
3. Standard and Smartphone	1 (4.00%)	0 (0.00%)	0 (0.00%)	1 (0.90%)		

4.7.4 *Preference of testing format for future assessments*

Overall, 81.4% of participants said they would prefer the standard testing method to be used at their next eye examination, while 11.5% chose the smartphone and only 0.9% choose both the standard test and smartphone testing. The majority of females (83%) and males (80%) chose the standard testing for future testing with a smaller proportion of females and males (16% and 20%, respectively) opting for smartphone testing.

Similarly, when stratified for age groups, the majority, in any age group, chose the standard testing (Figure 4.5). For those whose preference was the smartphone app testing in future, the highest proportion was from the youngest age group i.e. 28% from the 18 to 24 year olds (Figure 4.5).

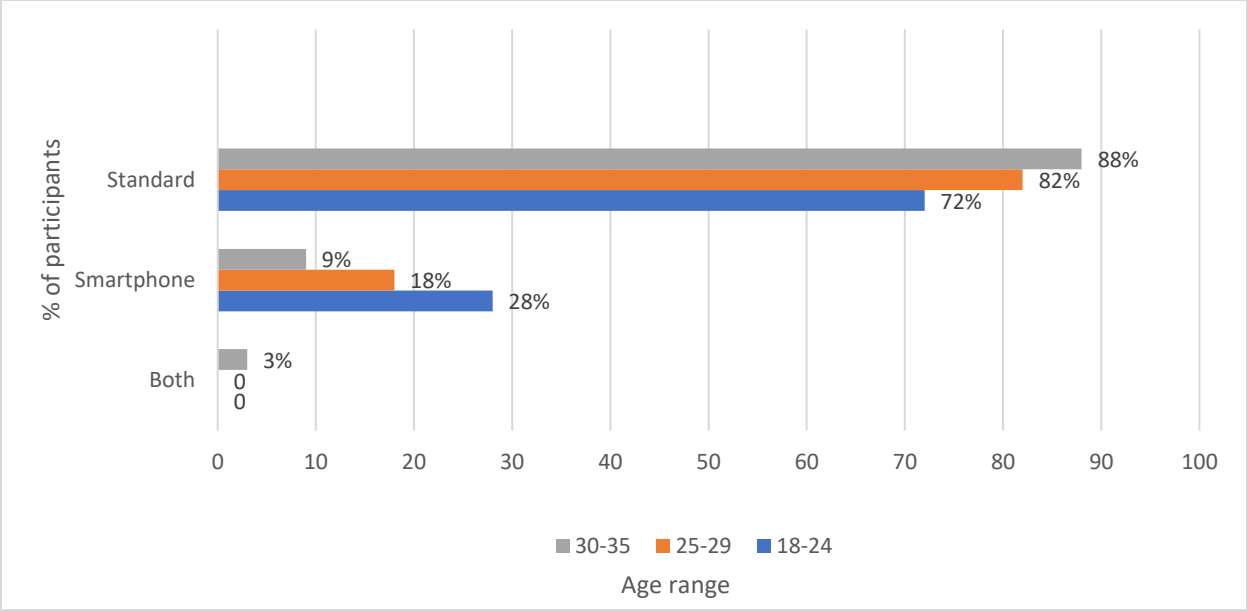

Figure 4.5: Preference of future testing method according to age groups.

For those that chose the standard test as their preferred method, the reason for choosing this option was the majority of participants felt that this testing method was more reliable (38.1%) and familiar (27.4%) to them. Those that chose the smartphone testing chose this option as their preferred testing method because it was more interactive (15.0%).

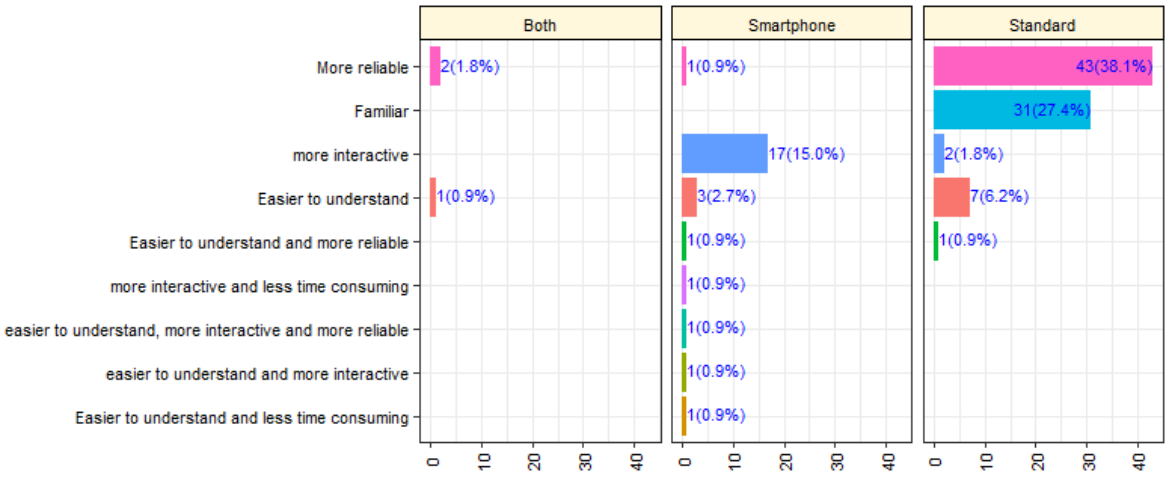

Figure 4.6: Reasons for preference of future testing method

4.7.5 *Smartphone application tests*

The last segment of the questionnaire centered around the participants' perceptions of the smartphone apps only, with the responses illustrated in Figure 4.7.

The majority of participants (63.7%) found the astigmatism app test to be the easiest to use and understand, followed by CS testing (25.7%) and then VA (8%). A small number (2.7%) reported that all three tests were equally easy to use and understand.

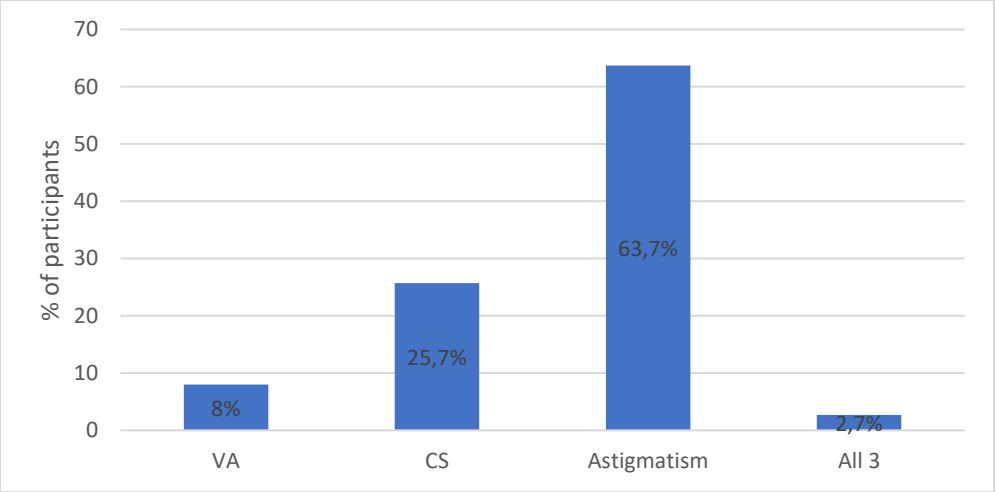

Figure 4.7: Ease of use and understandability of Smartphone tests

The reason for selecting the astigmatism test as being the easiest to use and understand could be because the majority (87.6%) of participants found the astigmatism test to be the most interactive and displayed the most interactive visuals. The astigmatism app tests also proved to be the app most of the participants (71.7%) found to have the easiest instructions to follow, while only 23% and 5.3% chose CS and the VA test respectively to have the easiest instructions (Figure 4.8).

In terms of duration of testing, VA testing was reported by the majority of participants (83.2%) with the remaining 16.8% finding CS testing to have taken the longest. Almost all of the participants (99.1%) indicated that they were able to understand and interpret the astigmatism test results with a very small percentage (0.9%) claiming to have understood CS results. No participant could understand the VA test results.

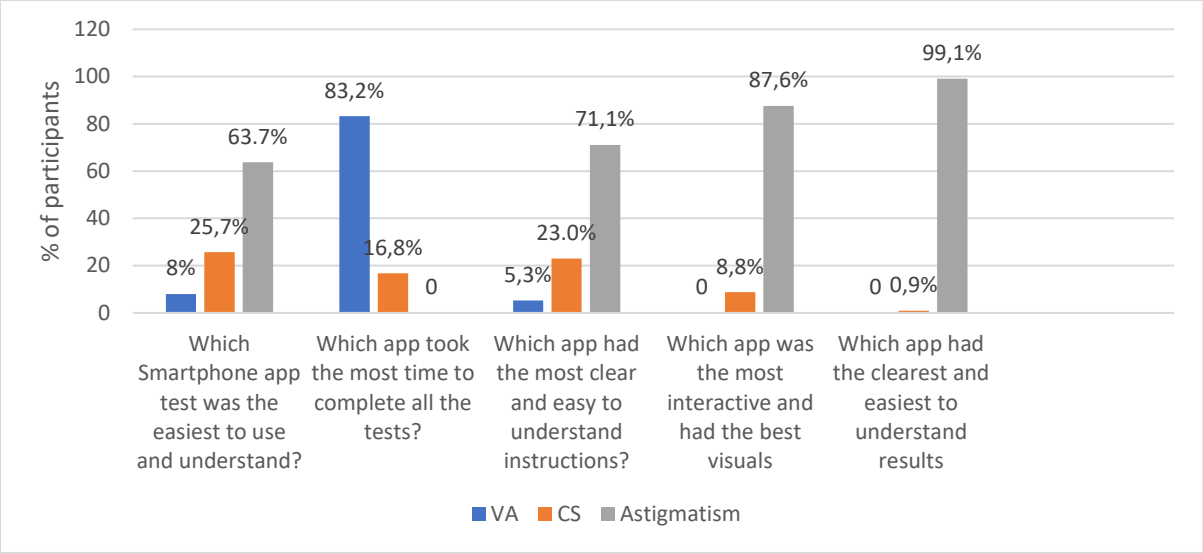

Figure 4.8: Participants' perceptions of the different smartphone applications for assessment of vision

Participants perceived the Smartphone app tests to be accurate as is seen in Figure 4.9, as the majority believed that the results were either extremely accurate or fairly accurate (9.7% and 87.6%, respectively). This was the case for 99% of females and 96% of males.

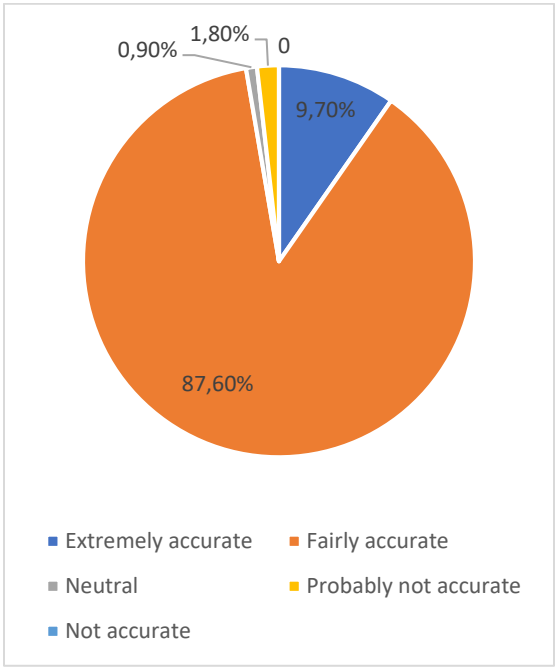

Figure 4.9: Participants' perceptions of accuracy of results from Smartphone application testing

As the majority of participants found these apps to have fairly accurate results, most participants (88.5%) are fairly comfortable to rely on these results to determine their visual status, while 8% are extremely comfortable and only 2.70% are not comfortable to rely on these app test results (Figure 4.10). Out of the 88.5% that were fairly comfortable, 88% were females and 89 % were males. Those that chose extremely comfortable, 9% were female and 7% were males.

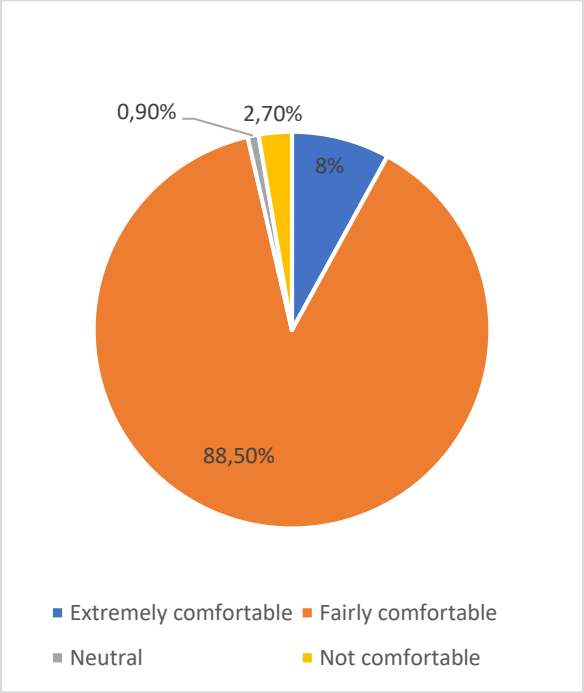

Figure 4.10: Participants' comfort with relying on these Smartphone applications to determine their visual status

4.8 CONCLUSION

The majority of the participants in this study where female (61.1%) from the Black/African (44.2%) race group with an approximate age of 27 ± 56 years. Many participants were also frequent computer users (53.1%).

After analyzing the standard and smartphone apps for testing distance VA, the standard test appeared to have results most similar to the Paid app (Kay iSight test professional®). However, when comparing all three tests results the mean difference was always less than 0.1 hence, showing no clinically significant difference between the three tests.

The Smart Optometry® (Free app) was found to overestimate the CS results however, the results compared most similar to the Standard Pelli-Robson test for testing CS, while the Paid app (Variable contrast sensitivity®) was found to significantly overestimate the CS results.

Both the free (Eye Meter®) and paid (Eye test®) astigmatism Smartphone apps were found to underestimate the number of participants having astigmatism when compared to the standard JCC test.

Overall, a large portion of the respondents in this study preferred the standard testing procedure over the smartphone apps. Participants occupation or gender did not influence this decision.

The astigmatism app test overall, outperformed the VA and CS testing in ease of use, clear instructions, most interactive and easiest understanding results. Overall, participants reported the smartphone test to have fairly accurate results and were fairly comfortable to rely on these results to determine their visual status.

CHAPTER FIVE

DISCUSSION

5.1 INTRODUCTION

This chapter critically analyzes the findings of the current study in relation to the research question and previous studies in related fields. The first section discusses the demographics of the participants and compares it to regional and national demographic statistics thereby providing a description profile. Thereafter, the results obtained for the comparison of the three visual parameters assessed in this study i.e. VA, CS and astigmatism with smartphone apps to standard clinical testing is critically analyzed. Wherever possible the main study results are compared to similar past studies. The chapter concludes with the discussion of the participants' perceptions of smartphone vision testing to clinical testing based on the results of the questionnaire.

5.2 DEMOGRAPHICS

Overall, the demographics of the participants was reflective of South Africa in terms of gender, age and race. The gender profile of the participants in the current study was in keeping with that of South Africa in general (StatsSA, 2017) with a greater proportion of females (61.1%) than males (38.9%), however it differed slightly from that of the Western Cape, where the study was carried out, which is closer to that of the total world population having almost equal numbers of females (51%) and males (49%) (The World Bank., 2019). A possible reason for this bias could be because of the use of convenience sampling strategy which involved using a sample of the population which was close at hand and not necessarily an accurate representation of the actual population. As gender bias could possibly lead to distortion of results and the sample not being representative of the study population (WHO, 2004), it is always preferable to use random sampling where samples are chosen strictly by chance (Foley., 2018).

The Google Mobile App Report of 2017 (https://www.ipsos.com/sites/default/files/2017-08/Google-mobile-apps-report-2017.pdf) reported interesting trends based on the gender of mobile users. In general, the survey found an equitable distribution of female and male users (50% each). Therefore, one would not expect a significant difference in the use of apps for health testing between the genders. However, when considering the content of the smartphone apps, a greater number of males using apps for sports compared to females (75 % versus 25%, respectively) was noted in the report. On the other hand, women, of all ages, are the major app users as compared to males and whether it be to register on new apps, online purchases or subscriptions there is a greater percentage of women engaging in these apps. The same source confirms that almost 9 out of 10 female smartphone users engage in apps. These trends may explain the greater proportion of females in the

current study sample as this gender may have agreed to participate in the current study more readily as the focus of the study is an area quite familiar to them.

The median age of the participants in the current study was 27 years which is very similar to the predicted median age of the South African population for 2020 being 27.6 years (Plecher, 2019) making the study largely applicable to the South African population. However, considering the average age of app users is reported to be approximately 36 years (Google Mobile App Report., 2017) the sample in the current study may represent a slightly younger generation. The age range selected for the current study (18 to 35 years) was, however, deliberate particularly as millennials (ages 18-34 years) are more willing to pay for mobile apps, with one third of them purchasing more than one app per month (MindSea, 2019). Furthermore, it was recorded in 2017 that 36% of millennials purchased five or more apps, while just 3% of users aged 55+ users did the same (MindSea, 2019). The age range of the current study therefore is reflective of mobile app users.

The latest population statistics in South Africa (StatsSA, 2019) report that the Black African race group makes up the largest population group (80.8%), followed by Mixed Race (8.8%), Caucasians (8.0%) and then Indians/Asians (2.5%). This distribution was fairly consistent with the demographic profile of participants in the current study with the exception of a slightly higher number of Mixed Race participants and Caucasians (31.0% vs 21.2%, respectively) which is more reflective of the study area (Western Cape) where the demographic profile includes approximately 42.4% Mixed Race and 15.7% Caucasians (Cape Town population., 2020).

Based on occupations, the majority of participants in the current study were classified as engaging in "high computer use" making the sample fairly appropriate for the assessment of smartphone vision screening as this group of individuals have been identified in the literature as the most likely to use such apps. Generally, these frequent computer users belong to a group of people that are well educated and earn a comfortable salary. A study by Smith (2015) stated that people who are graduates or have relatively higher education levels and earn a higher salary are the individuals who are most likely to use these smartphone apps as their health is a priority to them and secondly because they have the skill and confidence to operate health apps on their smartphones. Carroll (2017) also confirms that health app users are younger, more educated, willing to take care of their own health and have a higher income, and therefore more likely to use health apps.

5.3 REFRACTIVE STATUS

The majority of the participants were found to have low myopia (near-sightedness) with low astigmatism. Furthermore, the majority of the participants that took part in this study were high computer users which links up to the suggestions that near-sightedness could be attributed to the high amounts of accommodation of

prolonged near work (Po-Wen *et al*., 2019). In today's working society the majority of office workers are compelled to spending long hours in front of a digital screen which has resulted in patients even emmetropes or patients with low prescriptions (<0.50 DS or DC) complaining of sore, tired and strained eyes, these patients often benefit from an accommodative support lens or a single vision near lens to alleviate those symptoms.

5.4 DISTANCE VISUAL ACUITY ASSESSMENT

The main indicator of visual impairment due to vision loss can be identified using Visual acuity (National Research Council, 2002). Visual acuity (VA) and the concept of 20/20 vision is well known among most individuals when it comes to testing their vision and hence, if one had to experience blurry or distorted vision the VA test will be the 'go-to' test to be performed. Because this is the main test used to screen their vision, it is important for any testing apps to able to do this with a fair amount of accuracy as often people may rely on the findings to make decisions on the need to seek further eye care or not.

The accuracy of the Pocket Eye Exam® (in this section referred to as the Free App) and the Kay iSight Test Professional® app (in this section referred to as the Paid App), for assessing distance VA (DVA) was assessed by comparing the results obtained with the apps to that produced by a standard optometric distance vision assessment with a Snellen chart. The smartphone apps were found to provide very similar measurements for DVA to the standard clinical method when considering the median DVAs recorded. When considering the pass/fail criteria for DVAs, however, significantly more participants failed the distance vision assessment, for either eye, with the Snellen chart compared to both the free and paid Apps. As a lower decimal notation value implies poorer DVA the implication is that both apps overestimated the DVA. A possible reason for the overestimation in the instance of the Free App was the Snellen letters were presented at larger scale increments. There were only seven rows of VA measurements ranging from 6/60 to 6/6, missing out on some important VA values and hence, possibly overestimating the VA measurements. The Paid App had smaller increments of VA values and had a total of 16 rows of letters ranging from 6/150 to 6/3.8 which could give a more accurate VA result. The developers of the Free App could improve the accuracy of the app by increasing the number of rows for DVA measurements.

Similar findings were reported by De Venecia *et al*. (2018) who found Peek Acuity® (a smartphone VA app) to overestimate the subject's VA thereby giving the patient a measurement that did not warrant a follow-up eye examination. Tofigh *et al*. (2015) attributes the overestimation of VA with smartphone apps to the contrast ratio of the iPhone when equated against the standard test. Furthermore, the Early Treatment Diabetic Retinopathy Study (ETDRS) reported the contrast ratio of a clean printed Snellen or VA chart/card to be below 33:1, whereas an iPhone 5 has a contrast ratio of 1151:1 and was given as the reason for the discrepancy in near VA readings between a smartphone and a near vision card (Tofigh *et al*., 2015). It is known that VA

measurements can be enhanced by increasing the contrast of the testing chart or screen (Sheddy *et al*., 1984). While the actual contrast differences between the Snellen chart and the Free and Paid Apps, used in the current study were not measured, visibly there was a difference. Moreover, while the contrast of the smartphone on which the apps were used can be varied, that of the Snellen chart was fixed. The reliability and validity of VA measurements with smartphone apps thus can be enhanced by specification of the contrast level to be used with the app.

When assessing clinical measurements, it is important to consider clinically significant differences in addition to statistically significant differences. In terms of DVA, even a one-line difference in VA can be considered to be clinically significant when considering certain visual tasks. For example, in order for a monocular patient to obtain a code 8 (EB) driver's license in South Africa a minimum of 6/9 (0.6 in decimal notation as it would appear on a VA chart) Snellen VA in the functional eye is required in addition to other visual field requirements (Vision Optometrist, 2018). One line poorer than this would be the 6/12 (0.5 in decimal notation) which is a difference of 0.1. Thus a 0.1 difference in overestimation of VA produced by a screening app would have passed the individual as having the legal VA for driving preventing them from having a further vision assessment, when in actuality the individual may need spectacles in order to drive on the roads safely. It is for this reason that a difference of DVA of 0.1 in decimal notation was considered clinically significant. It must be noted though that, in the current study, the difference in DVAs obtained by the different methods were consistently less than 0.1 as indicated in the median values, thus being both clinically and statistically insignificant making the DVA measurements produced by the apps acceptable for the assessment of DVA.

Sensitivity and specificity are statistical measures of the performance of a test. The test's sensitivity, which is theoretically the true positive rate (TPR), is an indicator of the ability of a test to detect those individuals that actually do have a disease or condition (Stephanie, 2014). The importance of a test that is highly sensitive can be advantageous for ruling out a disease as it correctly picks up patients who have the disease. The specificity of a test, on the other hand, is theoretically the true negative rate, correctly identifying those people without the disease or condition (Stephanie, 2014). Specificity is equally important as a highly specific test can be beneficial for eliminating patients who do not have the disease. Stephanie. (2014) has suggested that sensitivity and, or specificities of between 70-80% are generally acceptable, however other studies (Budere *et al*., Malhotra *et al*., 2010) have cautioned that the sample size and prevalence of the condition being investigated must also be taken into account when determining what the acceptable sensitivity or specificity for a test is. If the sample size is too small it may produce skewed estimates and a wastage of resources. The study sample was as determined under the guidance of a statistician and thus assumed to produce fairly accurate sensitivity and specificity values.

The sensitivity of both the Free App and Paid App in the current study was greater than 75% irrespective of which eye was considered implying the ability to provide accurate measurements in those patients with reduced DVA. In addition, in the current study, the specificity of both the Free and Paid Apps for DVA measurements was over 95% irrespective of which eye was considered, implying the test could accurately identify participants with good vision. These findings thus indicate that these apps are able to pick up visual impairment and therefore, are useful at minimum for purposes of vision screening for VA. As no other study was found that reported the sensitivity and specificity of smartphone apps for the assessment of distance VA, no further comparisons can be made.

5.5 CONTRAST SENSITIVITY

Contrast sensitivity is the ability to identify minute discrepancies in shading and patterns and plays a major role in detecting objects without clear outlines and differentiating objects/details from their background (Alia *et al.*, 2012). Contrast sensitivity testing often is not performed routinely in an eye exam (all about vision, 2019) yet it is of great clinical value. Cataracts are the leading cause of preventable blindness worldwide (Lee *et al.*, 2016). Unfortunately, patients with cataracts only present when they encounter a reduction in their VA, which they able to detect even in their homes, impacting their functional performance. However, in these patients, a decrease in CS may be experienced even before a reduction in VA (Arden, 1978). In addition, CS is an accurate measure of visual defect such as glaucoma which is one of the leading causes of irreversible blindness globally (WHO, 2004) and is able to differentiate the different grades of diabetic retinopathy and cataracts (Habtamu *et al.*, 2019).

Other than for the detection of ocular disease, research has shown that reduced CS may also impact on visual comfort during daily tasks like reading or watching television (Heiting, 2019). Furthermore, it can affect the ability to drive safely at night as it leads to difficulty in seeing pedestrians walking alongside poorly lit streets (Heiting, 2019). In the elderly, poor CS also can increase your risk of a fall if you fail to see that you need to step down from an unmarked kerb and steps (Katz *et al*., 2019). Access therefore, to a simple and fast app that can screen for this aspect would be very valuable. In addition, it is important that these screening devices provide accurate results as there is a risk of potential misdiagnosis of sight threating eye conditions.

The measurement of CS moreover, better characterises functional vision than high contrast VA alone and subsequently has been used effectively as a tool to identify deteriorating visual function early on in conditions such as diabetes, glaucoma and macular degeneration (Di Leo *et al.*, 1992; Keane *et al.*, 2010). It is those patients who have 6/6 VA but still complain of "misty" or "flat" vision that CS testing is most useful in (Arden., 1978). Despite the benefits of CSF testing, it is seldom performed in a clinical setting because of the time and specialist equipment needed.

The assessment of CS by Smart optometry® (in this section referred to as the Free App) and Variable Contrast sensitivity® (in this section referred to as the Paid App) iPhone app was compared to that obtained with the standard Pelli-Robson chart. It must be noted though that while the standard Pelli-Robson chart provided an actual score for CS, the free and paid apps only provided a percentage CS with no indication of whether it is a pass or fail. A table with the exact conversion of the Pelli-Robson score to percentage could not be located, however, the normal values as outlined in the Pelli-Robson manual was used to grade the results of all tests (Pelli-Robson and apps) in terms of fail and pass criteria. According to the manual while a score of 2.0 indicates normal contrast sensitivity of 100 percent, a score of 1.5 is consistent with visual impairment thus a score of less than 1.65 was regarded as a fail for CS (Aziz.,2014).

More participants, for both the right and left eyes passed the CS testing with the free and paid apps as compared to the standard Pelli-Robson test indicating a high overestimation rate by the apps. This implies that some participants who had reduced CS were missed by the apps. The overestimation of results by the apps could have been attributed to the difference in chart generation i.e. one being printed and the other two computers generated, rather than the design of the chart being the issue. The standard Pelli-Robson chart was a printed chart that was held at one meter from the participant. The chart was used in normal room illumination (1300 lux) (wozniak *et al*., 1999). The chart was positioned perfectly parallel to the patients face and the room lighting illuminated the chart evenly to ensure there was no unnecessary reflections off the chart. In contrast, while the free and paid apps used the same Pelli-Robson design, the Free App consisted of eight rows of six capital letters each. The top letters of the chart were seen in high contrast with the contrast gradually reducing towards the bottom of the chart. The user was asked to tap and call out the faintest letter that was visible. The Free App letters were randomised so when the participants were selecting the last visible letter there could not have been a chance of memorisation. The Paid App had five constant letters reducing in contrast from 100% to 1.25% so there is a chance the participant could have memorised the letters and recalled the same letters for finer contrast levels even though the letters may not have been visible to them which could have resulted in this app overestimating the number of users passing this test. A possible suggestion to the developer of this app is to randomize the presentation of letters at each contrast level to prevent memorization, a second alternate is to start with 0% contrast and increase the contrast level until the participant is able to recite the letters correctly. This may ensure more accurate results from the Paid App.

A similar trend was noted by Zeri *et al*. (2018) who found that a computer LCD Pelli- Robson test overestimated the CS significantly, irrespective of the eye tested, when compared to a printed Pelli–Robson clinical chart used at both one and at three meters ($p < 0.01$). They therefore concluded that computer-generated versions of the Pelli–Robson chart did not provide accurate results when compared to printed version of the Pelli–Robson printed chart.

The Free App, for both the right and left eyes, demonstrated relatively higher specificity than sensitivity values. This suggests that the Free App was better at detecting individuals with normal CS than those with reduced CS. The Paid App on the other hand, while demonstrating good specificity showed very low sensitivity of less than 50% implying that this app was not useful in identifying users with poor CS often passing these individuals. These findings of sensitivity and specificity however have to be considered in relation to the sample size and in this case have to be interpreted with caution particularly as the study did not include subjects with ocular pathology in whom this test is more relevant.

5.6 ASTIGMATISM

Astigmatism is a type of condition whereby the eye does not focus light rays on the retina due to an irregular cornea resulting in distorted and blurred vision, additionally other symptoms of astigmatism include eye strain, headaches, squinting and eye irritation (Heiting, 2018). The ability of Eye test® (in this section referred to as the Paid App) and Eye Meter® iPhone apps (in this section referred to as the Free App) to detect the presence of at least 0.50D of astigmatism was assessed in relation to the results obtained from the JCC test in the subjective refraction.

While more than half of the participants were found to have at least 0.50D of astigmatism in either eye with clinical JCC testing, a significant percentage of participants having astigmatism were missed by both the Free and the Paid App indicating a high underestimation rate. Both apps were thus found to be ineffective in detecting astigmatism.

The JCC test involves a detailed procedure in determining the amount of astigmatism. It comprises of several steps to determine firstly the axis of the astigmatism and the associated cylindrical power. These steps ensure that the final cylinder power is an accurate representation of the astigmatism the patient has. Both the Free and Paid apps astigmatism tests utilised a ‘Fan and Block' astigmatism wheel which merely screens for the presence of astigmatism. The fan-and-block technique is less utilised in practice nowadays because it is less sensitive at determining small cylinders and a person with a head tilt will not give accurate results (Optician, 2014). Because this test is found to not be sensitive for detecting small cylinders both apps often were unable to detect small degrees of astigmatism in the participants.

The detection and correction of even small amounts of astigmatism is important as it is a condition in which the eye does not focus images appropriately, however it may not always result in a significant decrease in vision unlike in the case of spherical refractive errors. For this reason, it may prevent a person from considering or seeking an eye test. Yet, in addition to blurred vision, other debilitating symptoms such as eye stress or strain, squinting, poor night vision, eye irritation, headaches, fatigue and difficulty focusing while reading may

occur with astigmatism (Campbell., 2019). Furthermore, astigmatism is reported as having a major effect on the common daily task of night driving with problems like glare from the headlights of oncoming cars or halos around streetlights being attributed, to some degree, to uncorrected astigmatism (Larson, 2020). The implication of this can be on the confidence of individuals when engaging in night driving and subsequently on road safety impacting themselves and other road users. Hence, while it is not necessary that screening apps be able to quantify accurately the amount of astigmatism, it is valuable for these screening tests to be able to at minimum, detect the presence of astigmatism so that further testing may be sought.

The sensitivity and specificity of the Paid App for results in the right eye could be determined, and was found to indicate good sensitivity but fair specificity implying that it may have been able to correctly detect those that had astigmatism but was not as good in correctly identifying those that did not have astigmatism. The left eye for the Free App showed a high sensitivity result indicating this test maybe useful in identifying astigmatism. As no other study was found that assessed the screening for astigmatism using smartphone or other apps, no further comparisons can be made.

5.7 PERFORMANCE OF FREE APP VERSUS PAID APP

Further analysis of the results was performed to see how the paid apps performed relative to the free apps in trying to determine whether payment for an app means it probably has undergone more intense development. The DVA measurements produced by the Paid App (Kay iSight Test Professional® Chart) was more comparable to the Snellen chart measurements than the Free App, with the Free App consistently overestimating DVA. The sensitivity of the Free App for DVA measurements was lower than that obtained with the Paid App.

For the assessment of CS while both apps tended to overestimate the CS as compared to the standard test, the Free App results were more comparable to the standard test. In addition, while the specificity of both the Free App and Paid App were similar, there was a large difference in their sensitivities with that of the Paid App being much lower. These results must be interpreted with caution though due to the sample size. The presentation of letters in the Free App were randomised making it difficult for any user to recall the same letter twice hence, giving a more accurate result of the users CS due to the inability to memorize the letters. With the Paid App, because the letters presented for each contrast level was the same, this could have resulted in many participants calling out the letters based on memorisation and not by actually seeing those letters clearly, resulting in a high overestimation of participants passing that test.

Furthermore, it must be noted that the cost of the Paid App was R299.00 and it was a relatively expensive CS app to purchase. It may therefore be assumed that it was more developed in terms of superior quality software, imagery and contrast control and therefore able to provide more accurate results than the Free App. However,

this was not the case as the Paid App considerably overestimated the CS in the participants, which again may have been related to the presentation of the test targets as explained above.

While both the Free and the Paid App underestimated the number of participants having astigmatism when compared to the JCC test, for both the right and left eyes, the Free App appeared to miss more of the astigmatism than the Paid App. This could be of concern as the app will be passing those participants who have astigmatism and who ideally may need to have a full eye examination. On closer inspection, the Free App astigmatism chart is a combination of a dark blue background and light blue wheel lines. This unusual low contrast presentation of the astigmatism wheel could the reason why participants did not recognise any of the lines (axis) being darker than the others and, hence passed the test. The Paid App, however, has a high contrast white background with a black astigmatism wheel. This presentation of the chart was most likely easier for the participants to recognize which lines were darker which resulted in the Paid App producing relatively similar results to the standard JCC test.

A survey of the number of free mobile apps downloaded in comparison to the number of paid mobile apps downloaded worldwide in the period 2011 to 2017 show a significantly greater preference for free mobile apps (Blair, 2020). This difference can most likely be attributed to cost. Anecdotal evidence suggests that one may expect a paid app to be more sophisticated in its design and development hence the cost and therefore would have more accurate results when compared to a free app which may not be as well developed. The current study has found that both the Free and Paid Apps were accurate enough for DVA assessment but inadequate for the assessment of CS and astigmatism. The cost of an app therefore seems to be determined arbitrarily and at this stage is not an indication of accuracy.

5.8 PERFORMANCE ON SMARTPHONE APPLICATIONS ACCORDING TO GENDER

When looking at the smartphone VA testing, overall, females were found to have more comparable median VAs than males when compared to the standard VA test. This testing procedure was also chosen as the smartphone app test that took the longest time to complete as noted in the questionnaire. A report by Response Source (2011) stated that males tend to be more impatient than females. This could possibly be a reason why females had better VAs because they took more time to think and give the VA answers. The test that took the lesser time to complete was the astigmatism and CS tests. For these tests, participants were merely stating if any lines on the astigmatism wheel looked darker and for the CS test calling out the last visible letter. Because these tests possibly took less time to complete males were also found to perform equally well and hence, possibly showing patience level affects responses by different genders. From the above results however, there does seem to be a relationship between patience levels of different genders to giving response for the app testing and this ultimately could affect the results of different tests.

5.9 QUESTIONNAIRE

The participants' perceptions of using the smartphone apps compared to standard clinical testing was determined using the questionnaire which all participants completed after undergoing both the standard clinical routine and app testing.

5.9.1 Preference of testing format

The questionnaire uncovered that the majority of the participants preferred the standard testing procedure over the smartphone testing and the main reasons for choosing the standard testing option was they found it to be the most reliable and familiar option to them. These findings are in keeping with the assertion by Wicklund (2018) that despite national trends of healthcare systems launching consumer telehealth programs, people still prefer the personal touch of an office visit with a doctor as they consider in-person exams to be more beneficial. This may explain why the majority of participants in the current study preferred the standard test over the apps as they were probably more comfortable with direct optometric eye examinations rather than testing with the smartphone apps. It was clearly not because of lack of understanding as the majority of participants indicated that both platforms (standard clinical test and the smartphone apps) were easy to understand.

This preference of a standard clinical test is given credence by numerous studies (Perera *et al*., 2015; Tofigh *et al*., 2015; De Venecia *et al*., 2018) that have found standard tests to produce more accurate results than the app tests researched. It was therefore not surprising that the majority of participants choose the standard test as their preferred testing option for their next eye appointment again citing reliability and familiarity for this choice. These findings, however, may also have been influenced by other factors including participants wanting to "please" the researcher who was also the testing optometrist, by showing preference to standard clinical testing; as well as not being as familiar with smartphone testing as they were with an in-person eye testing. Future studies should thus consider including participants who use smartphone testing regularly.

For the minority (23%) of participants that chose the smartphone as their preferred testing option, the main reason for this preference was that it was more interactive than the standard clinical test. Wicklund (2018) reported additional reasons for wanting a virtual platform including convenience (26%) as they liked the option of skipping trips to and from the doctor's office, access healthcare in the comfort of their home (25%), quick access (20%) and short waiting times (16%).

While no significant difference in choice of future testing was noted between females and males, or when considering the amount of "computer usage" as determined by occupation, when preference was further stratified according to age it was found that the older age group (30-35 years) was more likely to choose the standard test and the younger group (18-25 years) to choose the smartphone app tests, even though the "older"

group in the current study was still relatively young. Kruse *et al.* (2017) reported that the elderly are hesitant to change and consider familiarity as the main reason for choosing the standard test which is in alignment with the assertion by Ward. (2013) that attraction to the familiar is a common and pervasive pattern in all of us. This motivator, familiarity, may also explain why the younger participants were relatively more likely to choose the smartphone apps for future testing. The younger generation spends more time using mobile apps than people who are older and millennials are three times more likely to be excited about new mobile apps and features than older users (Mindsea, 2019).

5.9.2 Preference of smartphone application test

Overall, the apps for assessing astigmatism proved to be the easiest to use and understand, easiest instructions to follow, displayed the most interactive visuals and took the least time to complete. After closer inspection of the astigmatism app wheel, it clearly showed a more interesting graphic presentation than the VA and CS charts in the other apps. The reduced time duration to complete the astigmatism test could also be a possible reason why the majority of the participants (63.7%) choose the astigmatism test as the easiest app to use. The astigmatism app had the most concise and understandable instructions and the results were given in an easy to understand pass and fail criteria. All of these factors could have contributed to this finding of the astigmatism app being perceived as the best.

It was surprising to note that almost all participants (99.1%) could understand and interpret only the astigmatism test results, while many had difficulty with understanding and interpreting the results of the DVA and CS apps. Considering these smartphone apps are intended to be used as home screening devices, no participant could understand the VA test result because the result is given in 6m Snellen notation. Also, a very small percentage of participants (0.9%) were able to understand the CS result because the result is given in percentage notation which does not mean much to the user as to what is normal and what is not. These results are meant to guide users on whether they require an eye examination or not and if the user is not able to understand the results this could result in major misinterpretation and possible under referral of patients. This aspect of smartphone apps must therefore receive careful consideration and revision particularly with a feature to indicate to the user whether further detailed testing is required or not.

Even though 40.7% of participants preferred the standard test over the smartphone testing, 87.6% of participants believed these apps to provide fairly accurate results with most of them (88.5%) indicating being fairly comfortable to rely on these results to determine their visual status. However, multiple studies (Pereira *et al.*, 2015, Tofigh *et al*., 2015 and Zeri *et al*., 2018) have reported smartphone VA and CS tests to be unreliable and inaccurate.

5.10 CONCLUSION

Mobile apps play a central role in people's daily routines. According to Blair. (2019), 91% of smartphone owners use apps therefore this feature should be explored as a means of increasing access to vision assessment, with at minimum being used for vision screening.

Visual acuity testing is an important indicator of vision and more especially visual impairment and any test used for this purpose should provide accurate results. The Kay iSight professional® (Paid) and Pocket Eye Exam® (free) VA app testing overall showed promising results and with some adjustments could be used for future VA screenings.

The CS and Astigmatism app testing however, were not as promising with the CS apps overestimating the results and the astigmatism app testing significantly underestimating the number of participants with astigmatism. If all four smartphone apps are to be used for screenings, developers are required to relook at the tests with respect to proper calibration, contrast, design and sizing.

Even though smartphone testing has become widely popularized, the participants in this study seem to still prefer the standard testing option. Even though this was indicated as their preferred testing platform they still find smartphone app testing to be accurate and are comfortable to rely on these app findings as indications of their visual status.

It can be concluded that smartphone eye testing has become widely popularised with their multiple screening apps however, both optometrists and developers need to ensure correct contrast ratio, brightness, optotype size and proper instructions by the app are provided by all screening apps to ensure the results are accurate and reliable. There definitely needs to be more studies done and should focus on validation of these apps before they can be used safely to screen individuals for visual deficiencies.

CHAPTER 6

CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

This chapter concludes with a synopsis of the main findings of the current study, in addition to highlighting the limitations identified following a critical analysis of the results produced. It also outlines recommendations for future studies particularly in the area of e-Health as it relates to eye care.

6.2 CONCLUSIONS

i. The Kay iSight Test professional (Paid) VA app results compared closely to that produced by the standard Snellen test. The Pocket Eye Exam (free) VA app slightly over estimated the VA results but the difference was not clinically significant. Overall, both apps showed promising results and with some adjustments could be used for future distance VA screenings.

ii. The Variable Contrast Sensitivity (Paid) app and Smart Optometry (Free) apps significantly over estimated the CS results when compared to the standard Pelli-Robson test. Further modifications and thereafter validation of both apps is required before it can be used for CS screenings. However, it provides an important tool considering the value of CS testing in the early detection of vision disorders.

iii. The Eye test (Paid) app and the Eye Meter (Free) apps tend to underestimate the number of participants with the presence of astigmatism when compared to the standard JCC test. These tests need further modification before they can be used in screening for the presence of astigmatism.

iv. Overall, the participants in this study chose the standard test over the smartphone test as their preferred method of visual testing for two main reasons viz. reliability and familiarity. Even though they chose the standard test, the participants perceive these apps as producing fairly accurate results and are comfortable to rely on these results to determine their visual status.

6.3 LIMITATIONS

i. This study utilised convenience sampling, which involved the use of participants which were close at hand and therefore is not necessarily an accurate representation of the general population. This type of sampling method creates various biases including a gender bias towards females as in the current study, which could possibly lead to findings which cannot be generalized to the population

at large. None of the participants in the current study had any significant ocular pathology and the performance of these apps in this category of user would have been useful.

ii. The findings from this study only hold true for the six apps tested on the iPhone 6 plus and may not be generalised to all iPhone screens because the uniformity of colorimetric and photometric properties of all iPhone devices differ.

iii. Different smartphone apps displayed their results in different notations which could have differed from the standard clinical test making direct comparison and interpretation thereof, difficult. This resulted in the researcher having to find methods to convert the results into one notation that was the easiest to interpret and draw comparisons.

iv. Optotype sizes, contrast and testing distances were not consistent between all the apps, and although it can be assumed the apps are properly calibrated, this could potentially affect the results.

v. Participants were asked to complete a total of six app tests during one clinical visit. While the durations of the apps were short, this could have been strenuous on the participants, in some cases, due to visual fatigue, which could have compromised the results.

vi. The iPhone used was always set to maximum brightness and this might produce a glare effect in some participants and a possible after-image which could contaminate results hence, it is imperative the app states the optimum brightness for performing the test.

vii. Smartphone optometric app testing is a fairly new area of vision screening. For the majority of participants in this study this was their first encounter with vision screening apps which could have resulted in them being anxious, second guessing their answers and wanting to provide "correct" answers to satisfy the examiner which could have potentially affected the results.

viii. Dishonesty of participants when completing visual tests on the apps, as well as on the standard clinical tests.

ix. Dishonesty of participants when completing the questionnaire impact the reliability of the results.

6.4 RECOMMENDATIONS

i. Future studies should consider using random sampling to select their study sample. This would facilitate representation of the general population and limit certain biases. The study population should include both people that use apps for vision testing currently, as well as those that do not thereby allowing for group comparisons.

ii. This study only used an apple iPhone 6 plus as the device to administer the various apps. It is possible that using these apps on other brands of smartphones, iPads or other LCD devices which differ in luminance properties, contrast ratios, screen sizes and retina display, may produce different results. It is therefore recommended that developers determine and indicate which devices are most compatible and suitable in ensuring optimal use of the optometric apps.

iii. Phone brightness can certainly affect the contrast and clarity of an image on the screen. In this study the brightness was set to maximum since none of the apps stated a specific brightness level. To ensure the most reliable results, apps need to detail the correct settings like brightness levels for the different devices in order for the test to perform optimally.

iv. All testing apps should be user friendly i.e. the testing instructions should be easy to understand and the test results should be self-explanatory to ensure it is easily understood. There must be a code set in that advises the user on the need for a comprehensive vision examination or not, at the end of the programme.

v. As all tests are performed on both the right and left eyes, as well as binocularly, apps should randomise the presentation of the letters to prevent any chance of memorisation which will affect the accuracy of the app testing.

vi. Developers should consider using these apps to assess other aspects of vision such as stereopsis, colour vision, macular integrity and visual field defects as these tests can be useful for patients to manage conditions like glaucoma and age-related macular degeneration.

vii. The study in question was performed on participants with no known ocular pathology hence, the results are only valid for “healthy” eyes. Other studies should include participants with known ocular pathology to see if the results produced are reliable.

viii. Interdisciplinary studies involving both information technology and health care professionals should be conducted to assess the validity as well as the reliability of all smartphones-based apps. Proper calibration of optotype design, size, testing distance and contrast needs to be agreed upon by both optometrists and IT developers to ensure the most accurate and reliable testing apps are developed. In this way app testing can become a vital tool in facilitating the delivery of eye care.

ix. For future studies it would be recommended that all participants refractive error be classified according to their different grades and thereafter, compare the grades to the usefulness of the apps.

x. The age range of the participants in the current study was off a youthful age (18-35 years). Future studies are recommended to wider the age range to determine how effective the apps are for different age groups.

6.5 CONCLUSION

The use of mobile devices for the delivery of health care has expanded rapidly in the last decade. Today, more than ever, people are relying on their smartphones to take care of all their needs with individuals increasingly taking an active interest in personalised health care particularly motivated by convenience and affordability. There are numerous smartphone apps available on the iStore and Google play store, however, considering the literature that was studied, there are very limited studies on the accuracy of these smartphone apps.

Smart-Technology visual testing can radically improve the way individuals take an active role in personalised vision care by utilising these devices for home self-vision screenings. They not only can be used for vision screenings but also can be used for monitoring visual changes especially in people with pathological conditions such as glaucoma and AMD. These devices will also be of tremendous use in rural and remote areas where access to ophthalmic care is limited. Certain vision tests such as contrast sensitivity are not routinely performed due to high expense of the specialised charts used. In these instances, the smartphone apps would serve as an appropriate alternative as a screening measure for clinical use.

The optometry industry has always been subject to intense regulations to ensure that patients receive the best possible care with accurate diagnosis and treatment. Smartphone-based optometry testing should be no different yet, currently, there are limited published studies on the accuracy and reliability of these applications. Factors such as lighting, target distance and target size need to be controlled in order for these tests to produce accurate results. This type of testing medium can revolutionise the optometry industry enabling the provision of eye care services to many more people, at a faster rate and be more cost effective, however these smartphone tests need to be validated first before their use can be optimised.

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APPENDICES

APPENDIX 1:

Information Document

Date: _____

Greetings

I am a qualified Optometrist, currently pursuing my Master's degree at Westville campus at the University of KwaZulu-Natal. My research is entitled "**Comparability of selected iPhone optometric screening applications to equivalent standard optometric tests".** This study aims to determine if smartphone applications for vision assessment are comparable to results produced by the equivalent standard optometric tests.

Research is just the process to learn the answer to a question. This research is not intended to treat or cure any medical condition or disease.

You are being invited to consider participating in this study that comprises of two parts.

Part 1: Involves the researcher performing standard optometric tests on you as well as using smartphone applications to conduct multiple optometric tests.

Part 2: Will involve you completing a questionnaire that contains questions relating to the standard optometric tests, as well as, the use of the smartphone optometric tests. It should take about 5 minutes for you to answer the questions

The study is expected to enroll a minimum of 100 people. I am not being paid to do this study. It is a requirement as per the Postgraduate Masters optometry education at the University of KwaZulu Natal.

Participation in this study involves the completion of the standard optometric tests, smartphone application tests as well as the study questionnaire. The study will not provide any direct benefits to you, the participant other than the visual assessment, but it will help me gain more knowledge on the accuracy and reliability of smartphone optometric testing. Participation in this study will not compromise your level of health care received at this institution.

Participation in this research is voluntary and you may withdraw participation at any point of the study. In the event of refusal/withdrawal of participation you will not incur penalty or loss of treatment or other benefits to which you are normally entitled.

We will not pay or give you anything if you participate.

This study does not record your name or address – just a study number. We will protect confidentiality of personal/clinical information always.

This study has been ethically reviewed and approved by the University of KwaZulu-Natal (approval number_____).

In the event of any problems or concerns/questions you may contact the researcher at Therisha Moodley (083 708 7052), or the UKZN Biomedical Research Ethics Committee, contact details as follows:

BIOMEDICAL RESEARCH ETHICS ADMINISTRATION

Research Office, Westville Campus

Govan Mbeki Building Private Bag X 54001 Durban 4000 KwaZulu-Natal, SOUTH AFRICA Tel: 27 31 2604769 - Fax: 27 31 2604609 Email: BREC@ukzn.ac.za

Supervisor Contact Details:

1. Dr. R. Hansraj

Email: hansrajr@ukzn.ac.za

2. Ms. P Govender

Email: p.govender@brienholdenvision.org.za

Consent to participate in Research

I, _____ have been informed about the study entitled" Comparability of selected iPhone optometric screening applications to equivalent standard optometric tests" by Therisha Moodley.

I understand the purpose and procedures of the study.

I have been given an opportunity to ask questions about the study and have had answers to my satisfaction.

I declare that my participation in this study is entirely voluntary and that I may withdraw at any time without affecting any treatment or care that I would usually be entitled to.

If I have any further questions/concerns or queries related to the study I understand that I may contact the researcher; Therisha Moodley (083 708 7052).

If I have any questions or concerns about my rights as a study participant, or if I am concerned about an aspect of the study or the researcher then I may contact:

BIOMEDICAL RESEARCH ETHICS ADMINISTRATION

Research Office, Westville Campus

Govan Mbeki Building Private Bag X 54001 Durban 4000 KwaZulu-Natal, SOUTH AFRICA Tel: 27 31 2604769 - Fax: 27 31 2604609 Email: BREC@ukzn.ac.za

_____ _____ Signature of Participant Date:

_____ _____ Signature of Witness Date: (Where applicable)

_____ _____ Signature of Translator Date: (Where applicable)

APPENDIX 2:

Questionnaire

Instructions to answer the questionnaire:

- This questionnaire is to determine your perception of Smartphone application tests to standard Optometric tests.
- The questionnaire consists of 13 questions (please answer all honestly) and should take you approximately 5 minutes to complete.
- Use a tick (√) to choose your option, and for some questions you may tick (√) more than one option.

Age: _____

Gender:

Male	Female

Race:

Black	Coloured	Indian	White

Occupation: _____

Standard Optometric testing vs Application testing:

1. Which testing procedure did you prefer?	Standard Optometric testing	Smartphone Application			
2. Why did you prefer the above?	Easier to understand	More interactive	More reliable	Less time consuming	I don't know
3. Which testing instructions were easier to follow	Standard Optometric testing	Smartphone Application			

4. Which testing method would you prefer to be used at your next optometric eye test	Standard Optometric testing	Smartphone Application			

Smartphone application tests

5. Which Smartphone app test was the easiest to use and understand?	Eye Test	Smart Optometry	Vision scan	Test your eyes	
6. Which app took the most time to download onto your smartphone?	Eye Test	Smart Optometry	Vision scan	Test your eyes	
7. Which app took the least time to download onto your smartphone?	Eye Test	Smart Optometry	Vision scan	Test your eyes	
8. Which app took the most time to complete all the tests?	Eye Test	Smart Optometry	Vision scan	Test your eyes	
9. Which app had the most clear and easy to understand instructions?	Eye Test	Smart Optometry	Vision scan	Test your eyes	
10. Which app was the most interactive and had the best visuals	Eye Test	Smart Optometry	Vision scan	Test your eyes	
11. Which app had the clearest and easiest to understand results	Eye Test	Smart Optometry	Vision scan	Test your eyes	

12. How accurate do you think the application test results are?	Extremely accurate	Fairly accurate	Neutral	Probably Not accurate	Not accurate
13. How comfortable are you to rely on the results of these apps to determine your visual status.	Extremely comfortable	Fairly comfortable	Neutral	Not comfortable	

THANK YOU

APPENDIX 3:

Data Recording sheet

SUBJECT NUMBER #1

RESULTS SHEET

Visual Acuity	Snellen 6m visual acuity	Free app: Eye Test by Magostech	Paid app: Vision Scan
OD			
OS			

Contrast sensitivity	Pelli-Robson test	Free app: Smart optometry	Paid app: Vision Scan
OD			
OS			

Astigmatism	JCC	Free app: Eye Test by Magostech	Paid app: Test your eyes: Eyesight.
OD			
OS			

APPENDIX 4:

Ethical Clearance certificate

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

23 September 2020

Ms T Moodley (214523678)
School of Health Sciences
College of Health Sciences
therishamoodley@yahoo.com

Dear Ms T Moodley

Protocol: Comparability of selected iPhone optometric screening applications to equivalent standard optometric test.
Degree: MOptom
BREC REF: BE703/18

RECERTIFICATION APPLICATION APPROVAL NOTICE

Approved:	**23 January 2020**
Expiration of Ethical Approval:	**22 January 2021**

I wish to advise you that your application for recertification received on 15 September 2020 for the above study has been **noted and approved** by a subcommittee of the Biomedical Research Ethics Committee (BREC). The start and end dates of this period are indicated above.

- Sample size may not be further increased beyond planned size without an amendment.

If any modifications or adverse events occur in the project before your next scheduled review, you must submit them to BREC for review. Except in emergency situations, no change to the protocol may be implemented until you have received written BREC approval for the change.

The committee will be notified of the above approval at its next meeting to be held on 13 October 2020.

Yours sincerely

.....
Ms A Marimuthu
(for) Prof D Wassenaar
Chair: Biomedical Research Ethics Committee

APPENDIX 5:

Study site permission form

Danie Sevenster & Partners INC. T/A Specsavers St.Georges Mall

52 St. Georges Mall

Cape town CBD

Tel : 0214244064

Cell : 0724905149

Fax : 0866930699

Director Daniel Sevenster

Reg Nr. 2008/004690/21

Vat Nr 4610193700

I, DANIEL SEVENSTER, Franchisee/ store owner of the Spec-Savers St. Georges mall optometry practice have been informed about the study entitled **"Comparability of selected iPhone optometric screening applications to equivalent standard optometric tests "** by Therisha Moodley.

I understand the purpose and procedures of the study.

I hereby give Ms. Therisha Moodley permission to conduct her master's Research at the practice during the period of August 2018 to July 2019. I give her permission to approach patient's coming in for an eye consultation to take part in her study. I also give her permission to use all Optometric equipment necessary at the practice in conduction of her research.

Signature of store owner (Daniel Sevenster) Date : 20/11/18

Signature of Witness Date : 20/11/18

DANIËL SEVENSTER
52 ST. GEORGES MALL, CAPE TOWN
8000 021 4244064
OP 13684 701 7659

APPENDIX 6:

Manuscript 1-Submitted to Telemedicine and e-Health Journal.

A review of Smart-Technology Optometric Visual Testing Applications for assessing Visual Acuity and Contrast Sensitivity

Moodley, T[1], Hansraj, R[1] and Govender, P[1].

[1]Discipline of Optometry. University of Kwa-Zulu Natal, South Africa.

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Abstract

Background

The unprecedented use of mobile technologies, as well as advancements in their applications to address health and visual priorities, have evolved tremendously in the past decade. This innovative use of smart technology is being explored as a means to provide visual self-screenings as society today has displayed a keen preference to taking care of their needs at their convenience. This gives rise to a fairly new and rapidly advancing area of optometry which is smart-technology visual testing.

Method

A literature search was conducted using two main databases i.e. PubMed and Research Gate for peer review studies pertaining to smart technology optometry visual testing applications. Studies dealing with smartphone/ smart technology visual acuity, contrast sensitivity and astigmatism testing were included. A total of 17 articles published from 2013 up to 2019 were found and reviewed.

Results

Studies report the uptake and usage of smartphones as unprecedented. iPhone visual acuity screening applications have yielded accurate and reliable results especially the Peek acuity® test which also appears to be the most popular test. Studies on contrast sensitivity testing have mostly been noted on iPad devices with the majority reporting this form of contrast sensitivity assessment to be reasonably accurate.

Conclusion

Even though there has been rapid expansion in the use of smart-technology for visual screening, there is limited published studies on the validation of these smart-tech applications hence, questioning their accuracy and reliability leading to the reluctance of eye care professionals to use these apps in a clinical setting.

Introduction

Society today individuals prefer to take care of their needs at their own convenience hence resulting in the self-service industry growing by 81% in the last few years[1] with an important expansion into the health care arena including optometry. With the unprecedented spread of mobile technologies, as well as advancements in their innovative applications (apps), people are now able to perform vision screening tests on themselves at their own convenience. Moreover, these apps provide results to the patient about their visual status and feedback as to whether a full comprehensive eye examination with a registered optometrist is recommended. However, if these apps are to be adopted by eye care professionals, they must yield accurate and reliable results. If not, a misdiagnosis could lead to devastating visual outcomes which can ultimately impact on an individual's life.

Smartphone apps have been increasing in popularity with the number of consumer apps downloaded over the past two years increased from 300 million in 2009 to a staggering five billion in 2010[2]. There are 43,700 medical apps available in the Apple Store alone for physician and patient use with the caution that patients should be aware that not all medical apps are accurate with only approximately 54% of medical apps available on iTunes considered to be accurate[3].

The optometric industry has always been subject to intense regulations to ensure that patients receive the best possible care with accurate diagnosis and treatment, as it rightfully should be. Smartphone-based optometry testing therefore should be no different yet there are limited published studies on the accuracy and reliability of available apps. According to the Health Professions Council of South Africa (HPCSA), vision screening is an investigative procedure with the goal being to identify individuals in need of referral for a comprehensive examination. Similar rules pertaining to standard visual screening, should also apply to smartphone vision screening, as both entities aim to detect visual difficulties in individuals. Therefore, smartphone apps should not only be able to provide accurate and reliable results but also provide feedback as to whether the user needs a full comprehensive eye examination and possibly where this could be obtained.

There have been several studies[4,5,6,7]conducted to determine the accuracy of smart technology application testing however, the results vary significantly, with some studies[4,6,8,9,10,11,12,13,14,15,16,17],concluding these applications produce accurate results while others[5,18,19,20,21] report the opposite. These varied findings may be related to the use of different types of smart technology devices providing variations in contrast an lighting, as well as apps varying in terms of different types of test charts used. Since visual acuity testing is considered the standard psychophysical test of visual function used in many clinical settings there were relatively more studies in this area, however the findings were not always consistent. Paucity of studies in other clinical areas like contrast sensitivity may be due to this area not being frequently investigated in usual clinical settings hence unfamiliarity with this visual function, as well as that interpretation is complicated relative to visual acuity testing. Due to this unprecedented popularity of smartphone vision testing, more insight is required into the reliability of these tests which have the potential for increasing access to vision screening and subsequently seeking eye care timeously, for many.

Method

A literature search was performed using two electronic data bases i.e. PubMed and Research Gate. A combination of keywords, such as smartphone technology, iPhone, applications, visual acuity, astigmatism, contrast sensitivity and vision screening, in the form of title words or optometry subject headings, were used in the search. A final search was conducted on the 30th March 2020.

Articles dealing with the accuracy and reliability of both visual acuity and contrast sensitivity smartphone testing were of high importance. Studies dealing with the development and validation of new smart-technology applications were also among the top studies reviewed. Reference lists of all identified articles were cross checked to identify other relevant studies. This strategy was used to adopt other relevant articles used in previous reviews.

INCLUSION AND EXCLUSION CRITERIA

Studies that were conducted in the last 10 years and those that met the criteria for optometry application testing on smartphone or other technological devices were considered in addition to studies:

1. published in the English language.
2. including all age ranges, races and geographical locations.
3. with a participation rate of at least 70% of the total study sample.
4. clearly defining the term and use of Telemedicine and Smart-technology.
5. clearly outlining the benefits of telemedicine and how telemedicine has evolved over the years.
6. reporting the significant use of smartphone technology to manage patients' needs.
7. providing reliable statistics on smart- technology, number of available health applications and the number of users throughout the world.
8. outlining the benefits of smart-technology applications in the optometry and ophthalmology field.
9. comparing the use of smartphone visual acuity tests versus standard visual acuity testing. Different types of optometric apps were researched.
10. comparing the use of smartphone contrast sensitivity test versus standard contrast sensitivity testing. Different types of contrast sensitivity apps were researched.
11. comparing the use of smartphone astigmatism test versus standard astigmatism tests.
12. which found smartphone optometry testing to not be reliable or accurate.
13. developing and validating new smart-technology applications for visual acuity and contrast sensitivity testing.

Studies were excluded if:

1. they did not include visual acuity, contrast sensitivity or astigmatism testing.
2. there was no indication of informed consent being obtained from participants.
3. they were not relevant to optometry smartphone application testing.

4. they were published in languages other than English.

DATA EXTRACTION

The data extracted from each of the selected studies are illustrated in Table 1. The main data extracted were: region(s) in which the study was conducted, age group of participants, sample size and participation rate of each study, year in which the study was conducted, aim of the study, author(s) details, type of electronic device used for testing, name(s) of the specific apps tested, type of test chart used by each app, the notation in which the results were displayed, the main conclusion from the studies, with any recommendations made. Studies were grouped according to the visual parameter being investigated. This made analyzing and interrupting the data easier and less time consuming.

Results

After an extensive literature search, there was a total of 17 studies that met the inclusion criteria and were selected to be part of this review paper. The results are presented according to the focus areas of the studies.

ACCURATE SMARTPHONE VISUAL ACUITY TEST RESULTS

The Peek acuity® smartphone visual acuity test was found to be the most popular, and accurate and reliable for the assessment of visual acuity[4,8,9]. The Paxos Checkup® app was investigated by the Stanford Hospital Emergency Department (ED) and reported to be as accurate in determining emergency room patient's visual acuity when compared to readings obtained by the ophthalmologists which were regarded as the gold standard. The results interestingly revealed best corrected visual acuity (BCVA) measured by non-ophthalmic ED staff with an app to be more accurate than with a standard Snellen chart[12]. O'Niell., *et al* (2016)[11] assessed the validity of a visual acuity test using mobile technology devices in the primary care setting. This study, which assessed the VA of participants with a Snellen wall chart and two mobile technology devices (iPhone and iPad), reported a high level of general agreement between the Snellen chart and the testing modalities on the two devices. The study suggested that this newfound convenience should increase the frequency of visual acuity assessments, potentially identifying ocular or neurological pathology at an earlier stage and thus enabling timely and appropriate referral. Similar findings were reported by Han *et al*., (2019)[10] who compared the assessment of distance and near VA measurements using the V@home® mobile app with that obtained with the standard (ETDRS) chart, as minimal discrepancies between the two methods across all groups (0.010 to −0.100 logMAR). Therefore, the study concluded the V@home® app could accurately and reliably measure both distance and near VA. Moreover, the study also revealed 82.3 % of participants to be satisfied or extremely satisfied with the app with 72.5% indicating that they were likely or extremely likely to use the system again, further validating the app.

INACCURATE SMARTPHONE VISUAL ACUITY TEST RESULTS

Some studies by[5,18,19,20] have found smartphone visual acuity tests to be unreliable and inaccurate. All five studies were conducted on five different smartphone applications.

Even though there were many studies[4,8,9] confirming the accuracy of Peek acuity® test, the study by De Venecia *et al*., (2018)[5] found contradictory results. This study found that the Peek acuity® app tended to overestimate the VA of pediatric school children aged 6-16-years consequently reducing the possibility of them being referred for a full examination. This study concluded that this app could be made more accurate if the sensitivity (48%) would be improved.

Inaccuracies of VA measurements by apps were also reported by Pereira et al., (2015)[18] following an evaluation of the results obtained with a smartphone-based VA chart (Dr. Bloggs Ltd® running on an Apple iPhone 4) against that obtained with a standard 6 m Snellen VA chart at a university teaching hospital in Melbourne, Australia. The results showed a mean difference of two Snellen VA lines between the charts (0.276 logMAR). Of particular concern was the larger mean difference in logMAR acuity between the two methods in the subgroup of patients with Snellen VA worse than 6/18 (n=5). It was thus concluded that further validation of iPhone apps is required for the assessment of VA in patients particularly those with severe visual impairment. Another VA app (Eye chart pro app) proved to only be reliable for VA testing when the Snellen VA is better than 0.1 (20/200). This study [20] evaluated the accuracy of an app for the iPad (Eye Chart Pro®) as a portable method of VA testing. A total of 120 consecutive patients (240 eyes) underwent VA testing with an iPad 2 and with a conventional light-box chart. The logMAR VA results from the iPad reflected better VAs than those from the light-box ($P < 0.001$) hence overestimating the distance VA[20]. A similar overestimation of distance VA when using an iPad was found[13] when compared with the Early Treatment Diabetic Retinopathy Study (ETDRS) Tumbling E ($p < 0.01$) or Landolt C chart ($p < 0.01$).

Near VA measurement using the Eye hand book® smartphone application was compared to the conventional method of using a near VA chart[19] at the University of Texas medical branch eye clinic on 100 subjects. The study concluded that the Eye hand Book®, running on iPhone 5, overestimates the near VA by an average of 0.11 LogMAR units when compared to conventional near VA card. The recommendations made by the study was that eye care providers using portable high definition screens taking VA measurements should be mindful of potential disparity in VA measurements between different platforms.

ACCURATE CONTRAST SENSITIVITY RESULTS ON SMART-TECHNOLOGY DEVICES

Many researchers are trying to develop new and cost-efficient ways for testing contrast sensitivity as the general feeling is that contrast sensitivity function (CSF) is a better predictor of visual performance than high contrast VA alone and therefore, can better monitor the slow progress of eye blinding diseases[15,16]. Only one study was found that investigated contrast sensitivity on a smartphone device[6]. This study used the same technology as the Peek VA testing to develop and validate a smartphone Peek CS (PeekCS®) test. The PeekCS® test was compared to the reference standard which was a Tumbling-E Pelli-Robson CS test (PRCS). PeekCS® showed strong repeatability which was comparable with PRCS. It also had a faster testing time (44.6 seconds) than PRCS (48.6 seconds). The study therefore concluded that this smartphone-based PeekCS® is a repeatable and rapid test, providing results that are highly comparable with the commonly used PRCS test.

Other studies found in this area involved an assessment of contrast sensitivity testing on other smart technology devices such as on an iPad and LCD computers. A study[14] aimed at determining the accuracy of an iPad Pelli-Robson contrast sensitivity test (ridgevue.com®). The study found that the iPad test showed good repeatability when compared to the standard Pelli-Robson test, therefore, it was concluded that this testing option could be a rapid and convenient alternative to some existing measures. Dorr *et al*., (2013)[16] developed and validated an iPad contrast sensitivity test which was found to be an efficient and 'easy-to-use' assessment of CS testing. The results demonstrated that the iPad test proved reliable at estimating sensitivities at specific spatial frequencies which were however not identified in the paper. The authors did however indicate that the maximal sensitivities, which were consistently less than 1% were observed at low spatial frequencies. This test also reliably identified changes in contrast due to different luminance levels and it was concluded that CS testing on an iPad was indistinguishable from that obtained with specialized laboratory equipment. The ClinicCSF®, a contrast sensitivity function (CSF) test to be used on an iPad was designed by Rodriguez *et al*. (2014)[15]. Two versions of the ClinicCSF® were tested i.e. v1 and v2 with the best agreement between the standard functional acuity contrast test (FACT) and ClinicCSF® found for version2 in all spatial frequencies.

Another study[17] aimed to validate the accuracy and inter-test repeatability of a near and distance mobile (iPad) app, the Aston contrast sensitivity® test. This study determined that the mobile apps (near more than distance, $p = 0.005$) recorded higher contrast sensitivity than the printed tests. Furthermore, the Aston near and distance apps proved to be valid, repeatable and a time-efficient method of assessing contrast sensitivity at multiple spatial frequencies. This study[17] asserted that paper-based charts are often limited in the number of stimuli they can present and require the examiner to manually implement and respond to feedback from the patient. Hence, clinical measurements of psychophysical contrast thresholds can only be assessed in broad discrete steps of spatial frequencies and contrast. Meanwhile computerized CSF testing equipment can render a multitude of grating stimuli of various frequencies and contrast and adopt complicated testing methods making their use multifunctional and less time consuming.

The most noticeable difference between an iPad/ LCD computer and an iPhone is the size, this however, plays a crucial role in how an application is presented on the intended screen. The screen in an iPad is much longer and wider when compared to an iPhone. The iPhone 6 plus has a 16:9 aspect ratio whereas the iPad has a 4:3 aspect ratio. The larger screen usually, but not always, means that the iPad has a higher resolution than the iPhone, which makes it difficult to resize some apps. The combination of the resolution and the aspect ratio means that running iPhone apps on the iPad can result in a stretched-out display or a black border surrounding the app display[21]. This means that not all iPhone apps can be run on an iPad and vice versa, as this will result in inaccurate results due to the screen sizes and resolution being incorrect. In reference to the assertion by Livingstone *et al*., (2016)[22] the discrepancies in contrast ratio, optotype, contrast and test luminance of devices can be a possible reason for the variation in CS measurements when using a smartphone device compared to standard clinical test and further that the results obtained by the CS studies on an iPad or LCD device cannot apply to smartphone apps. A similar study[23] also stated a possible reason for the difference in contrast values between a standard printed chart and a smart device could due to the luminance of

surrounding light. He asserted that ophthalmic practitioners using contrast sensitivity measurements with letter charts probably need not make special efforts to illuminate the standard test surround appropriately. However, practitioners using sinewave gratings, especially computer-generated sinewave gratings, to measure contrast sensitivity, may have their measurements affected by inappropriately lit task surrounds.

INACCURATE CONTRAST SENSITIVITY RESULTS ON SMART-TECHNOLOGY DEVICES

Only one study was found that reported an electronic contrast sensitivity testing to be inaccurate. The study[7] found that an LCD Pelli-Robson chart (electronic version) chart did not produce accurate results. The study aimed to evaluate the accuracy and repeatability of a computer-generated Pelli–Robson test displayed on a liquid crystal display (LCD) system compared to a standard Pelli–Robson chart. Two repeated measurements were taken with the printed Pelli–Robson test and with the LCD test at 1 and 3 m. The results revealed that the contrast sensitivity measured with the LCD resulted in significantly higher results than the printed Pelli-Robson both at 1 and 3m ($p < 0.01$). The study concluded that computer generated versions of the Pelli–Robson test, displayed on LCD systems, do not provide accurate results compared to the standard printed version. The study suggested clinicians should consider that Pelli–Robson computer-generated versions are not interchangeable with the printed version.

CHALLENGES WITH SMARTPHONE/ SMART-TECHNOLOGY DEVICES.

All smartphone applications are expected to give accurate and reliable results but there appears to be scope for improvement. Furthermore, despite the rapid expansion in Smartphone application testing, only approximately 54% of medical apps available on iTunes are judged to be genuine healthcare apps[3]. Even more worryingly only a small portion of optometric smartphone apps are currently affiliated with an academic institution or association and hence the reliability of the test results of these apps are questionable. In addition, the use of smartphones in the eye health sector has several challenges related to the regulations and standardization of performed tests[24].

Other limitations envisaged with the use of these smartphone devices are as follows:

vi. Brightness and contrast of smartphone screens differ, in order for these devices to produce equally correct results these factors need to be standardized[24].
vii. Target optotype size has to be perfectly calibrated in order to produce results that can be equated with its standard clinical test.
viii. Smartphone optometric tests usually are not dimensionally the same as standard tests, so the accuracy of the test results may differ if proper calibration is not implemented.
ix. Different smartphones have different screen sizes. All tests should be calibrated to the size of the smartphone screen, and if this is not possible, the app should state which smartphone is not compatible with the app.

x. Instructions given by the apps need to be accurate and easy to understand to ensure the user performs each test correctly.
xi. Using mobile devices to transfer data should be done securely using message encryptions to ensure patient confidentiality.

Discussion

My analysis of the literature that was researched, does confirm that the use of telemedicine and smartphone technology has not only been revolutionizing the optometry and ophthalmology sector but many of the other health care fields as well. There has been a rapid increase in the number of smartphone users in the last decade with a large proportion of these individuals using many health apps including those for vision testing, as many individuals are taking keen interest in personalized health care. Even though there are numerous apps available, studies have shown that not all apps are accurate hence the reliability of these apps are questioned. Many of the studies that have been researched suggest that further validations of these apps are required before they can be used as a screening tool or even an equivalent testing option to the standard clinical tests.

Smartphone applications used for visual testing has numerous visual tests on them such as visual acuity, contrast sensitivity and astigmatism tests. After analyzing all the data, I have found that that for visual acuity and contrast sensitivity testing there have been varied findings. No studies have been found for the validation of apps for the detection of astigmatism.

VISUAL ACUITY

Overall, it was very difficult to conclude if smartphone visual acuity testing produced accurate or inaccurate results as the findings of the studies varied. Some studies[4,8,9,10,11,12,13] confirm smartphone apps to produce accurate results while others[5,18,19,20] report to the contrary. However, after analyzing the studies that focused on app testing for visual acuity, it has been confirmed the Peek acuity® by far is the most popular and accurate smartphone visual acuity test available. It was very difficult to find multiple studies for each app however, the Peek acuity® smartphone test was the only one on which multiple studies had been conducted, with all except one[5] reporting the app to be highly accurate and reliable for visual acuity measurements. A brief overview of a number of visual apps was also done and considerable variation in the content, instructions given, optotype size and appearance, graphics and imaging, design of visual acuity test (Snellen test, logMAR test) and notation for recording measurement was noted. As the current database of studies on smartphone visual acuity testing is limited, more research is required particularly in determining if the applications are safe and accurate to use for visual screenings.

CONTRAST SENSITIVITY

Despite there being limited published literature on smartphone CS testing, there were a few studies on smart-technology CS testing. Therefore, there is a need to assess how comparable the results of smartphone applications are to conventional tests as studies have shown that electronic versions of

contrast sensitivity testing may not produce the same results as printed charts do. From the literature that was analyzed a general consensus was noted that electronic contrast sensitivity testing does produce reliable and accurate results. Many studies[6,14,15,16,17] all confirm accurate results using electronic versions of CS charts. When each app was visually inspected it was noted that different applications use different designs of contrast sensitivity charts including the Pelli-Robson chart and the FACT. Moreover, the notation of results, instructions and appearance of each test also varied. Similar to the smartphone visual acuity studies, the database of contrast sensitivity studies is limited particularly those on smartphone contrast sensitivity apps. This means that even though there are numerous contrast testing apps available on the iStore none of them have been validated, thus more research done on smartphone contrast sensitivity testing is required before these apps can be used by people for visual screening.

ASTIGMATISM

After extensive research there were no published articles on smartphone astigmatism testing. This area of study seems to be very new to the optometry smartphone industry. The "Fan and Block" chart seemed to be the most widely used method to test for astigmatism on a smartphone device. The results of the test are non-specific with the results simply displayed as a pass or fail. There is no validation of current apps for the detection of astigmatism and again if these devices are to be used for determination of the presence of astigmatism in a screening capacity, research studies are required in this specific area.

LIMITATIONS OF THE REVIEW

The following are limitations of the review:

1. Smartphone visual testing is new area in the optometry industry hence, there were insufficient published studies on smartphone apps for visual acuity and contrast sensitivity, with no study on the use of apps for the detection of astigmatism studies on all databases researched.
2. For each smartphone app there was only a single study with the exception for the Peek acuity test.
3. Each study used a different method of testing and with different testing charts so it was difficult to make direct comparisons.
4. There was insufficient statistics available on the accuracy or inaccuracies of smartphone visual testing.

Conclusion

Today, more than ever, people are relying on their smartphones to take care of all their needs with individuals increasingly taking an active interest in personalized health care particularly motivated by convenience and affordability. There is numerous smartphone app available on the iStore and Google play store, however, considering the literature that was studied, there are very limited studies on the accuracy of these smartphone apps. The optometry industry has always been subject to intense regulations to ensure that patients receive the best possible care with accurate diagnosis and treatment. Smartphone-based optometry testing should be no different yet there are limited currently published studies on the accuracy and reliability of these applications. Factors such as lighting, target distance and target size need to be controlled in order for these tests to produce accurate results. This type of testing medium can revolutionize the optometry industry enabling the provision of eye care services to many more people, at a faster rate and be more cost effective, however these smartphone tests need to be validated first before their use can be optimized.

Disclosure Statement

No competing financial interests exist.

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Appendix 7:

Manuscript 2- Submitted to Journal of Ophthalmic Epidemiology

Comparability of selected iPhone optometric screening applications to equivalent standard optometric tests for the assessment of visual acuity

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ABSTRACT

Introduction

Smart technology visual testing has become popular, especially smartphone visual acuity (VA) testing. This innovative use of smart technology is being explored as a means to provide visual self-screenings as society today has displayed a keen preference for taking care of their needs at their convenience. However, the accuracy and reliability of these tests have not been fully established.

Aim

To determine if the Kay iSight Test Professional and the Pocket Eye Exam for the assessment of distance VA are comparable to results produced by the standard Snellen VA test.

Method

A total of 113 participants were recruited using convenience sampling. The study employed a comparative research design that compared the results of two smartphone apps, a paid and free app, to the Snellen chart. The paid app was chosen with the assumption this test would be superior to a free app test. The standard VA was taken first with the Snellen chart followed by the two smartphone apps, the presentation of which were randomized. The results of all three tests were captured in 6m Snellen notation and the Wilcoxon Signed ranked test was used to assess for any comparisons.

Results

The median DVA as determined by the Snellen test and both VA apps as being the same (0.63) for both the right and left eyes. The higher the decimal value the better the DVA. The pass/ fail criteria showed a higher overestimation rate by the free and paid apps when compared to the Standard Snellen chart. The Median and IQR differences between both genders for the right and left eyes for all three tests were always <0.1 indicating

not even a 1-line difference in VA. Equally high sensitivity and specificity values were found for both the free and paid apps.

Conclusion

The Kay iSight professional (paid) and Pocket Eye Exam (free) VA app testing, overall, showed promising results as they produced results similar to the standard Snellen test and thus, with some modifications, could be used for future VA screenings. However, due to the lack of literature more studies need to be done before these devices can be used for home screenings or clinical use.

INTRODUCTION

Rapidly advancing technology has led to the healthcare landscapes of many nations undergoing a dramatic change over the past few decades. The use of technology to deliver health care from a distance, more correctly referred to as telemedicine (Alexander *et al*., 2011) has been demonstrated as an effective way of overcoming certain barriers to the delivery of health care particularly in rural and remote areas (Scott *et al*., 2016). Telemedicine for vision care has been growing and establishing itself as a changing entity in the eye care industry. Both the optometric and ophthalmology fields have, to some extent, adopted the use of telemedicine to offer their services to a larger consumer base. Closely linked to telemedicine, in the field of optometry, smartphones and mobile applications (apps) allow individuals to perform vision screening tests on themselves to determine if there is a need for further visual examination.

Visual acuity testing is the most commonly performed test in ophthalmic clinical practice and is by far the most well-known screening app available on the Apple App store and Google Play store. Visual acuity refers to the ability of the visual system to discern fine distinctions in the environment and is measured with printed or projected visual stimuli. The presence of excellent VA tells the examiner that, most likely, the ocular media are clear, the image is clearly focused on the retina, the afferent visual pathway is functioning, and the visual cortex has appropriately interpreted signals received (Levenson *et al*., 1990). Therefore, the accurate assessment of VA is important as it guides clinicians as to whether further investigations are required and can quantify changes to vision over time (Han *et al*., 2019).

Visual acuity can be measured rapidly and inexpensively, with low-cost charts such as the Snellen VA chart, Tumbling E chart and Early Treatment Diabetic Retinopathy Study (ETDRS) chart which are available commercially, online for printing and increasingly in apps for mobile devices (Brady *et al.*, 2015). Some of the VA apps available are the Peek Acuity, Vision@home and Eye Chart Pro VA. These VA apps are mostly screening tests and do not have diagnostic value. Smartphone visual testing allows individuals to perform vision screening tests on themselves and provide feedback as to their visual status based on their VA and whether further testing is required.

Reports from previous studies on smartphone VA testing appear divided as to whether it is accurate or not. There are many studies (Bastawrous et al., 2015, Rono et al., 2018 and Han et al.,2019) that confirm this new technology to produce accurate results which are comparable to the standard clinical VA tests but other studies (Tofigh et al., 2015, Zhang et al.,2016 and De Venecia et al., 2018) assert that further validation is required before these tests can be used for clinical purposes. In particular, there are certain areas of app testing such as contrast ratio, optotype size, design, screen brightness and testing distance that needs to be further validated to ensure these tests produce accurate and reliable results.

The medical community should not allow convenience and an affinity for new technology to trump the responsibility to collect accurate clinical data. There could be adverse consequences of inaccurate app performance, such as generating unreliable clinical data or displaying inappropriate information to patients which could have dire consequences on patients' visual well-being. The optometry industry has always been subject to intense regulations to ensure that patients receive the best possible care with accurate diagnosis and treatment. Smartphone-based optometry testing should be no different yet currently, there are limited published studies on the accuracy and reliability of these apps. Thus, before smartphone apps can be used for home screenings or clinical purposes they need to be validated for accuracy. This study therefore set out to determine if the Kay iSight Test Professional, which is a paid app, and the Pocket Eye Exam, which is a free app for VA screenings are producing results comparable to that produced by the standard Snellen VA test.

METHODOLOGY

A comparative research design was used to compare the VA measurements produced by the Kay iSight professional app and the Pocket Eye Exam app to that recorded with the standard Snellen VA test. This study was conducted at a private optometric practice. Convenience sampling was used to select 100 subjects aged 18 to 35 years, of any gender or race.

Data collection only commenced once relevant ethical clearance had been obtained from Biomedical Research Ethics Committee of the University of KwaZulu-Natal (BE703/18) and consent was obtained by each participant. The study adhered to the tenets of the Declaration of Helsinki. The distance VA of subjects was first determined using a standard Snellen chart projected on a screen 3 meters (m) away from the subject. The Snellen VA chart was chosen as this chart is the most widely available and allows easier display on projector systems. The VA measurements were taken monocularly first and then binocularly on each subject. The results were thereafter captured in 6m Snellen notation onto the data recording sheet.

After the full eye examination was completed, subjects were presented with the two smartphone apps to assess VA. An Apple 64 GB, iPhone 6 Plus using IOS 9 was used as the smartphone device wherein both apps were displayed. The Kay iSight Test Professional is an app that needs to be paid for before use and will hereon be referred to as the paid app. The Pocket Eye Exam was available at no charge to the user and will hereon be referred to as the free app. Both apps had a Snellen chart design but only the paid app results were in 6 m Snellen notation. The free app results were in feet notation and had to be converted into Snellen notation. The subject was not given any instructions on how the test is performed or what each test is testing. He/she had to read the instructions given by the app and perform the test accordingly. The only instruction that was given to the subject is that he/she must read the letters aloud. Once completed, the results were captured in 6 m Snellen notation for easy comparison to the standard Snellen test. Both app tests were performed on the right eye and the left eyes and then binocularly. Room lighting, screen brightness and test distance were controlled and standardized for each test.

RESULTS

A total of 225 distance VA measurements (right eyes (n = 113)); left eyes (n = 112)) from 113 participants were obtained using the standard 6m Snellen VA chart and smartphone apps. As the data was not normally distributed it was more accurate to review the medians as the measure of central tendency when making group comparisons.

Table 1 shows the median DVA in decimal notation as determined by the Snellen test and both VA apps as being the same (0.63) for both the right and left eyes. The higher the decimal value the better the DVA. Even

though the median was consistently 0.63 with all tests, the IQR for the free app (RE: 0.25; 1.00; and LE: 0.32; 1.00) and paid app (LE: 0.25; 1.00)) were slightly higher than the Snellen lower IQR.

As the data was not normally distributed the Wilcoxon signed ranked test was used to test for statistical significance for the differences in the DVAs obtained with the Snellen chart compared to both apps. It was found that the differences between the Snellen test and either app, irrespective of the eye, were statistically significant (p values <0.01). However, when the difference in IQR between the right eye measurements obtained with the Snellen chart compared to the free and paid app values, the IQR difference was always less than 0.1 decimal notation which would have indicated not more than a one-line difference in DVA. This was the same for the left eyes as well. This indicates no clinically significant differences in DVAs between the standard test and either app.

Table 2 showed females showed a constant median of 0.63 for the standard test as well as the two smartphone tests except for the median of the Left eye paid app which was slightly higher (1.00). Males also had a constant left eye median of 0.63 for the standard test and the free and paid apps, whereas the right eye paid and free app tends to have a higher median than the standard Snellen VA. Males had a lower median than females in the right eye for the standard test whereas both genders had the same median in the left eye. Females tend to have a higher median in the left eye than males for the paid app and males showed a lower right eye median than females for the free app. However, the median and IQR differences between both genders for the right and left eyes for all three test formats were always <0.1 indicating not even a 1-line difference in Snellen VA, which overall is not clinically significant.

Measurements for distance VA for all three tests were further categorized into a pass and fail (Table 3). A pass was regarded as a VA score of 0.63 (equivalent to 6/9) or less. This passing criteria value of 6/9 was selected because the minimum vision requirement for driving on South African roads is 6/9 hence, this is one of the most common tasks that most people will need to engage in and often would use vision screeners to assess their VA.

A higher percentage of subjects, when considering both right and left eyes, were able to pass the distance VA test with the free app when compared to the Snellen chart and the paid app, resulting in a relatively higher overestimation rate by the free app. The paid app was found to overestimate the number of participants, based on the right eye readings, that passed the DVA testing compared to the Snellen chart however, the overestimation was not as high as with the free app.

The free app showed higher sensitivity for the left eyes compared to the right eyes, while the specificity of the right and left eyes was found to be almost the same. Slightly higher values of sensitivity and specificity were found for the Paid App for the right and left eye (Table 4 a/b).

DISCUSSION

Visual acuity has traditionally been used as the primary indicator of the magnitude of functional impairment due to vision loss (National Research Council., 2002). Visual acuity and the concept of 20/20 vision is well known among most individuals when it comes to testing their vision and hence, if one had to experience blurry or distorted vision the VA test will be the go-to test to be performed. Because this is the main test used to screen their vision, it is important for any testing app to able to do this with a fair amount of accuracy as often people may rely on the findings to make decisions on the need to seek further eye care or not.

The smartphone apps were found to provide very similar measurements for distance VA to the standard clinical method when considering the median DVAs recorded. Furthermore, the sensitivity of both the free App and paid App in the current study was greater than 75% irrespective of which eye was considered implying good capability of the apps to provide accurate measurements in those patients with reduced DVA. The specificity of both the free and paid Apps for DVA measurements was over 95% irrespective of which eye was considered, implying the test could also accurately identify participants with good vision. These findings thus indicate that these apps are able to detect visual impairment and therefore, are useful at the least for purposes of vision screening for visual acuity. As no other study was found that reported the sensitivity and specificity of smartphone applications for the assessment of distance visual acuity, no further comparisons could be made.

When considering the pass/fail criteria for DVAs however, the values obtained for either eye with the Snellen chart was consistently lower than that measured by both the free and paid Apps, with the difference found to be statistically significant. As a lower decimal notation value implies poorer DVA the implication is that both apps overestimated DVA. A possible reason for the overestimation by the free app was the Snellen letters were presented at larger scale increments. There were only 7 rows of VA measurements ranging from 6/60 to 6/6, missing out on some important VA values and hence, possibly overestimating the VA measurements. The paid app had smaller increments of VA values and had a total of 16 rows of letters ranging from 6/150 to 6/3.8 which could give a more accurate VA result. The developers of the free app could improve the accuracy of the app by increasing the number of VA measurements.

Similar findings were reported by De Venecia *et al*. (2018) who found the Peek Acuity app (a smartphone VA app) to overestimate the subject's VA thereby giving the patient a measurement that did not warrant a follow-up eye examination. Tofigh *et al*. (2015) attribute the overestimation of VA with smartphone apps to the contrast ratio of the iPhone when compared to the standard test. Furthermore, the ETDRS reported the contrast ratio of a clean printed Snellen or VA chart/card to be below 33:1, whereas an iPhone 5 has a contrast ratio of 1151:1 and was given as the reason for the discrepancy in near VA readings between a smartphone and a near vision card (Tofigh *et al*., 2015). It is known that VA measurements can be enhanced by increasing the contrast of the testing chart or screen (Sheddy *et al*., 1984). While the actual contrast differences between the Snellen chart and the free and paid Apps, used in the current study were not measured, visibly there was a difference. Moreover, while the contrast of the smartphone on which the apps were used can be varied, that of the Snellen chart was fixed. The reliability and validity of VA measurements with smartphone apps thus can be enhanced by the specification of the contrast and brightness level to be used with the app.

When assessing clinical measurements, it is important to consider clinically significant differences in addition to statistically significant differences. In terms of DVA, even a one-line difference in VA can be considered as clinically significant when considering certain visual tasks. For example, for a monocular patient to obtain a code 8 driver's license in South Africa a minimum of 6/9 (0.6 in decimal notation as it would appear on a VA chart) Snellen VA in the functional eye is required in addition to other visual field requirements (VisionOptometrist., 2018). One line poorer than this would be the 6/12 (0.5 in decimal notation) which is a difference of 0.1. Thus a 0.1 difference in overestimation of VA produced by a screening app would have passed the individual as having satisfied the legal VA for driving preventing them from having a further vision assessment, when in actuality the individual may need glasses to safely drive on the roads. It must be noted though that, in the current study, the difference was consistently less than 0.1, making the DVA measurements produced by the apps not clinically significantly different than that obtained with the Snellen chart and thus acceptable for the assessment of DVA.

There were a few aspects of this study that prevent widespread generalization of the findings. Convenience sampling used to select participants in this study creates various biases including a gender bias towards females in the current study. As the testing was done on an iPhone 6 plus the findings may not apply to all iPhones. Different smartphone apps displayed their results in different notations which resulted in the researcher having to find methods to convert the results into one notation that was the easiest to interpret and draw comparisons. Furthermore, optotype sizes, contrast and testing distances were not consistent between all the apps. The iPhone used was always set to maximum brightness and this might produce a glare effect in some participants and a possible after-image. For the majority of participants in this study, this was their first encounter with vision screening apps which could have resulted in them being anxious, second-guessing their answers and wanting to provide "correct" answers to satisfy the examiner which could have potentially affected the results. However, this study does provide useful information in an area in which research is currently limited.

CONCLUSION

Rapid advancements in the use of mobile technology to deliver health care is unprecedented. The use of Smartphone apps can be used as an effective way of overcoming certain barriers to health care particularly in rural and remote areas where access to Ophthalmic care is limited. Today, more than ever, people are also relying on their smartphones to take care of all their needs with individuals increasingly taking an active interest in personalized health care particularly motivated by convenience, affordability and accessibility. There are numerous smartphone apps available on the iStore and Google play store, however, considering the literature that was studied and the final results of this study, it is clear there need to be more studies done on the accuracy of smartphone VA testing before it can be used optimally for either screening and/or clinical use.

DISCLOSURE STATEMENT

No competing financial interests exist.

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Table and figures

Table 1. Showing the Median DVA with interquartile range (IQR) in decimal notation obtained with the Snellen chart, free App (Pocket Eye Exam) and paid App (Kay iSight Test Professional)

	RIGHT EYES	**LEFT EYES**
	Median (IQR)	Median (IQR)
Snellen Chart	0.63 (0.20; 1.00)	0.63 (0.20; 1.00)
Free App	0.63 (0.25; 1.00)	0.63 (0.32; 1.00)
Paid App	0.63 (0.20; 1.00)	0.63 (0.25; 1.00)

Table 2: Showing the Median and IQR for distance VA in decimal notation according to gender.

	Median (IQR)			
	Female		Male	
	RE	LE	RE	LE
Snellen chart	0.63(0.20;1.00)	0.63(0.20;1.00)	0.50(0.18;0.80)	0.63(0.20;1.00)
Paid app	0.63(0.32;1.00)	1.00(0.32; 1.00)	0.63(0.24;1.00)	0.63(0.29;1.00)
Free app	0.63(0.20;1.00)	0.63(0.25;1.00)	0.57(0.20;0.80)	0.63(0.21;1.00

Table 3: Showing the frequency of pass and fail categorization of distance visual acuity obtained with the Snellen chart, free and paid app.

	RIGHT EYES		LEFT EYES	
	PASS (n) (%)	FAIL (n) (%)	PASS (n) (%)	FAIL (n) (%)
Snellen Chart	58 (51.3%)	55 (48.7%)	67 (59.3%)	45 (39.8%)
Free App	69 (61.1%)	44 (38.9%)	70 (61.9%)	42 (37.2%)
Paid App	63 (55.8%)	50 (44.2%)	67 (59.3%)	45 (39.8%)

Table 4a. Sensitivity and specificity of the Free App in comparison to standard VA test.

		Snellen VA (Gold Std)			
		True Pass		True Fail	
		RE	LE	RE	LE
Free App	Pass	42	39	2	3
	Fail	13	6	56	64
Total		55	45	58	67
		Sensitivity		Specificity	
		76%	87%	97%	96%

Table 4b. Sensitivity and specificity of the Paid App in comparison to standard VA test.

		Snellen VA (Gold Std)			
		True Pass		True Fail	
		RE	LE	RE	LE
Paid App	Pass	49	43	1	2
	Fail	6	2	57	65
Total		55	45	58	67
		Sensitivity		Specificity	
		89%	96%	98%	97%

Appendix 8:

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Comparability of selected iPhone optometric screening applications to equivalent standard optometric tests for the assessment of contrast sensitivity and astigmatism

ABSTRACT

Introduction

There has been an unprecedented spread in the use of mobile technology in the last decade including the provision of health care services. The eye care industry has also adopted the use of these innovative smart-technology devices to provide rapid, convenient and less time-consuming eye screenings through the use of applications (apps). These apps allow you to assess a number of visual function tests including CS and astigmatism. However, the accuracy and reliability of these tests have not been fully established.

Aim

To determine if the Variable Contrast Sensitivity smartphone application (app) and the Smart Optometry iPhone app produces results comparable to the standard Pelli-Robson test for the assessment of contrast sensitivity. This study also aims to determine if the Eye Test (Paid) app and Eye Meter (Free) app for the screening of the presence of astigmatism provides results that are comparable to a standard clinical test.

Method

The study employed a comparative research design that compared the results of two smartphone CS apps and two astigmatism apps to the standard Pelli-Robson and JCC tests, respectively. A total of 113 participants were recruited using convenience sampling. The results were analyzed using frequencies, logistic regression and the Wilcoxon Signed ranked test.

Results

More participants passed the CS test with the smartphone apps as compared to the standard Pelli-Robson test. Statistically significantly ($p<0.001$) lower percentages of participants were detected as having astigmatism by both smartphone apps when compared to standard clinical testing.

Conclusion

Both the smartphone apps overestimated the results and both astigmatism apps significantly underestimated the number of participants with astigmatism. These apps therefore did not provide comparatively accurate results to the standard clinical tests therefore further development and investigation is necessary before these apps can be used as screening and/or diagnostic tools.

INTRODUCTION

With the unprecedented widespread use of mobile technologies, as well as advancements in their innovative applications (apps), people are now able to use smartphones, Liquid Crystal Display (LCD) computers, iPads and other digital devices to perform health screenings on themselves. In today's society individuals prefer to take care of their needs at their own convenience hence resulting in the self-service industry, aided by the aforementioned devices, growing by 81% in the last few years[1] with an expansion into the health care arena including optometry. In the field of optometry, smartphones and mobile apps give individuals the opportunity to perform vision screening tests on themselves. Moreover, these apps provide results to the patient about their visual status, as well as feedback as to whether a full comprehensive eye examination with a registered optometrist is recommended.

Contrast sensitivity (CS) is one area of visual function testing that is available on smartphone apps. Contrast sensitivity is the ability to detect subtle differences in shading and patterns and is important in detecting objects without clear outlines and discriminating objects or details from their background[2]. In clinical practice CS testing can be performed using the Functional Acuity Contrast Test (FACT), Lea Symbols, MARS letter CS, low-contrast ETDRS chart and most commonly with the Pelli-Robson chart. With smartphone app testing the Pelli-Robson chart design is most frequently used.

Contrast sensitivity testing often is not performed routinely in an optometric examination because of the time required to perform the test and specialist equipment required[3] yet it is of great clinical value. Cataracts are the leading cause of preventable blindness worldwide[4]. Unfortunately, patients only present when they encounter a reduction in their visual acuity (VA). However, in these patients, a decrease in CS may be experienced even before a reduction in VA[5]. Moreover, CS is a sensitive measure of visual defects in glaucoma which is one of the leading causes of blindness globally[6] and is able to discriminate the severity of diabetic retinopathy and cataracts[7] Other than for the detection of ocular disease, research has shown that reduced CS may also impact on visual comfort during daily tasks like reading, watching television or night driving[8]. In the elderly, poor CS also can increase your risk of a fall if you fail to see that you need to step down from an unmarked curb and steps[9]. Access therefore, to a simple and fast app that can screen for this aspect of vision would be very valuable particularly in directing individuals to seek professional care before irreversible damage occurs. However, despite the usefulness of these CS tests using smart technology, it is important that these screening devices provide accurate results as there is a risk of potential misdiagnosis of sight threating eye conditions. The literature that was reviewed revealed positive results for the accuracy of smart-technology CS testing as the majority of the studies[10,11,12,13] reported this form of CS testing to produce accurate and reliable results which were equally comparable to standard CS tests. However only one of these studies by[7] were conducted on a smartphone app.

Another visual aspect that has been the focus of smart-technology apps is astigmatism. Astigmatism is a type of refractive error caused by the variations in the curvature of the ocular media thus the principal focal lines do not produce a point focus of light from an object on the retina thereby leading to blurred or distorted vision. This reduction in vision though may not be easily detected during visual

tasks but may present with other symptoms such as eye strain, headaches, squinting and eye irritation[8] which impact on visual comfort rather. In routine eye examinations astigmatism is determined using the Jackson cross cylinder (JCC) test when performing a subjective refraction. Smartphone astigmatism screening apps have been observed to generally employ a fan and block chart. After an extensive search of the literature it was noted that there are currently no published studies on smartphone astigmatism testing.

Paucity of studies in areas of both CS and astigmatism may be due to this area not being frequently investigated as most smart-technology studies are usually done on visual acuity (VA) testing. If these apps are to be used for visual screenings it is imperative that this technology be fully investigated and validated before it can be used for home screenings or clinical use.

This study therefore set out to determine if the Variable Contrast Sensitivity app and Smart Optometry iPhone app for CS testing produced results comparable to those of the standard Pelli-Robson test when assessing CS. Furthermore, the results produced by the Eye Test and Eye Meter app for astigmatism screening were compared to that obtained with the standard JCC test. This study will also report on the usefulness of smartphone apps for vision screening and recommend ways in which this technology can be improved for optimal use.

METHODOLOGY

Ethical clearance for this study was obtained prior to data collection and the study adhered to the tenets of the Declaration of Helsinki. Data was collected at a private optometric practice on a total of 100 subjects. Healthy individuals aged 18 to 35 years, of any gender and any ethnic group were selected using convenience sampling.

Contrast sensitivity assessment was achieved by the smartphone app "Variable CS test" which can only be downloaded once paid for, therefore it is hereon referred to as the Paid CS App while the Smart Optometry which was available at no cost, is hereon referred to as the Free CS App. The paid app was chosen with the assumption this test would be superior to a free app test. Both these apps were compared to the results obtained with the standard Pelli-Robson clinical test.

For the detection of astigmatism, the Eye Test app which had to be paid for and is thus hereon referred to the Paid Astig App was used, as well as the Eye Meter which was freely available and therefore hereon referred to as the Free Astig App. Again, the paid app was chosen with the assumption this test would be superior to a free app test. The results of these two apps were compared to the clinical measurement obtained with the standard JCC test.

All participants initially underwent a complete optometric examination including the assessment of CS with the Pelli Robson test and astigmatism with the JCC test. The Pelli-Robson test was used to assess CS at distance. The chart was placed approximately 1m from the participant. The chart consists of capital letters arranged horizontally which decrease in contrast with each subsequent line. The participant was assigned a score (the participant's Log CS) based on the contrast of the last group in which two or three letters were read correctly. The LogCS score was then matched using Table i below to get a corresponding contrast value. The contrast value was than multiplied by 100 to get a

percentage. It was necessary to convert the Pelli-Robson LogCS score to percentage because both the paid and free app tests results were given as a percentage contrast.

A LogCS score of 2.0 indicates normal CS of 100 percent, a score of 1.5 is consistent with visual impairment thus a score of less than 1.65 was regarded as a fail[14,15]. As both smartphone apps tests were used as a screening device, it was decided to represent the results as a pass/fail criteria.

The JCC test was performed using a fused cross cylinder and a standard procedure. An astigmatism value of 0.50D, was regarded as being clinically significant and confirming the presence of astigmatism. Both tests were done monocularly and readings obtained for both the right and left eyes of each subject.

After the full eye examination was completed, subjects were presented with the four smartphone apps to assess CS and astigmatism. An Apple 64 GB, iPhone 6 plus using IOS 9 was used as the smartphone device wherein both apps were displayed. The subject was not given any instructions on how the test is performed or what each test is testing. He/she had to read the instructions given by the app and perform the test accordingly. The only instruction that were given to the subject is that he/she must read the letters aloud. The app tests were performed on the right eye and the left eyes and then binocularly. Room lighting, screen brightness and test distance were controlled and standardized for each test.

Both the Paid CS and Free CS app used a Pelli-Robson test design, however the results were displayed in a percentage notation and had to be converted into LogCS using Table 1. Both astigmatism apps had a fan and block chart design and the results were displayed as either pass or fail.

RESULTS

CONTRAST SENSITIVITY

More participants, for both the right and left eyes, passed the CS test with the Free and Paid CS Apps as compared to the standard Pelli-Robson clinical test (Table ii). A pass in this study was regarded as a contrast score of 1.65 and better[15]. Any value less than this was regarded as a fail. When the apps were compared to each other, more participants passed with the Paid CS App than the Free CS App. Logistic regression analysis found there to be statistically significant differences. The Free CS App compared more closely to the standard Pelli- Robson ($p<0.001$) test result than the Paid CS App ($p=0.345$) which tended to overestimate the CS results for both the right and left eye when compared to the Pelli-Robson chart results. All three tests, for both the right and left eyes, produced statistically significantly different CS ratings (p values <0.01) as per the logistic regression analysis.

When stratified according to gender the same trend of the Free CS App results comparing more closely to the Pelli-Robson clinical test results was noted for both females and males. When considering the results for the right eyes, a much larger percentage of males (90.9%) passed CS testing with the Paid CS App than females (82.6%), with similar findings for the left eyes (Table iii).

The free app showed much higher specificity than sensitivity when screening for contrast sensitivity, in relation to the Pelli-Robson chart, for both the right and left eyes (Table iva).

The sensitivity of the Paid App for both the right and left eyes (Table ivb), in relation to the Pelli-Robson chart was much lower than its specificity as well as, lower than the sensitivity of the Free App. However, the Paid App had very high specificity values for both the right and left eye.

ASTIGMATISM

More than half of the participants had at least 0.50D of astigmatism in the right (59.3%) and left (61.1%) eyes as determined with the standard JCC test. Statistically significantly ($p<0.001$) lower percentages of participants, as determined by the chi squared test, were detected as having astigmatism by both the Free and the Paid Apps for astigmatism (Table V).

While both the Free and the Paid Astig Apps underestimated the number of participants having astigmatism when compared to the JCC test, for both the right and left eyes, the Free Astig App appeared to miss more of the astigmatism than the Paid Astig App.

When the results were further stratified according to gender, similar results were noted. In comparison to the JCC test, both apps underestimated the number of females and males that presented with astigmatism (Table VI). Again, the results provided by the Paid Astig App was a little closer to that of the JCC test in both genders, compared to the Free Astig App.

The specificity of the Free App in the right eye was low (45%) (Table VIIa) however, the left eye had a high sensitivity. A 45% specificity of the right eye indicated this test was not good at identifying those participants with no astigmatism.

With the Paid App, the right eye had an equally high sensitivity and specificity (Table VIIb). The left eye had a very low sensitivity (36%) indicating this test is not adequate in identifying individuals with astigmatism.

DISCUSSION

The assessment of CS better characterizes functional vision than high contrast VA alone and subsequently has been used effectively as a tool to identify aspects of visual function in conditions such as diabetes, glaucoma and macular degeneration [16,17]. Despite its usefulness, CSF testing in a clinical setting is rarely done due to the time and specialist equipment required. Astigmatism is also another refractive condition with severe visual implications like blurred, distorted vision and eye strain. If left untreated if can have severe impact on visual comfort and ultimately daily functioning of an individual. Smartphone technology offers the potential for decreased CS and the presence of astigmatism to be easily screened for by the individual themselves, and thereafter seek further care if required.

More participants, for both the right and left eyes passed the CS testing with the Free and Paid CS Apps as compared to the standard Pelli-Robson clinical test indicating a high overestimation rate by the apps. This ties in with both the paid and free apps having low sensitivity values implying that some subjects who had reduced CS were missed by the apps. Logistic regression analysis found there to be statistically significant differences between the clinical test and the smartphone apps and the differences may be related to the difference in chart generation i.e. one being printed and the other two, computer generated. The Free and Paid CS Apps both used the same Pelli-Robson design as the

standard clinical test, however, the Free CS App consisted of eight rows of letters and six capital letters per line. The most noticeable difference between the standard Pelli-Robson test and the Free App was the lack of spacing between the couplets. The white LCD background was also quite bright for some participants which could have possibly affected the results. The top letters of the chart where of high contrast letters and they reduced in contrast towards the bottom. The user was asked to tap and call out the faintest letter that was visible. The letters in the Free CS App were randomized so when the participants were selecting the last visible letter there could not have been a chance of memorization. On the other hand, the Paid CS App had five constant letters reducing in contrast from 100% to 1.25% so there was a chance the participant could have memorized the letters and recalled the same letters for finer contrast even though the letters may not have been visible to them. This could have resulted in the Paid CS App passing more participants and overestimating the number of users passing this test. A possible suggestion therefore to the developers of this app is to randomize the presentation of letters at each contrast level to prevent memorization, with an alternative being to start with 0% contrast and increase the contrast level until px is able to identify the letters correctly. This may produce more accurate results from the Paid CS App.

A similar trend was noted by[18] who found that a computer LCD Pelli- Robson test overestimated the CS significantly, irrespective of eye used, when compared to a printed Pelli–Robson clinical chart used at both 1 and at 3 m ($p < 0.01$). They therefore concluded that computer-generated versions of the Pelli–Robson chart did not provide accurate results when compared to printed version of the Pelli–Robson printed chart.

The Free CS App, for both the right and left eyes, demonstrated relatively higher specificity than sensitivity values. This suggests that the Free CS App was better at detecting individuals with normal CS than with reduced CS. The Paid CS App on the other hand, while demonstrating good specificity showed very low sensitivity of less than 50% implying that this app was not useful in identifying users with poor CS often passing these individuals. These findings of sensitivity and specificity however, have to be considered in relation to the sample size and in this case have to be interpreted with caution.

While more than half of the participants were found to have at least 0.50D of astigmatism in either eye with clinical JCC testing, a significant percentage of participants having astigmatism were missed by both the Free and the Paid Astig Apps indicating a high underestimation rate with the apps. Both apps were therefore appeared to be ineffective in detecting astigmatism.

The JCC test involves a detailed procedure in determining the amount of astigmatism. It comprises of several steps to determine firstly the axis of the astigmatism, as well as the cylindrical power. These steps ensure that the final cylinder power is an accurate representation of the astigmatism the patient has. Both the Free and Paid Astig Apps utilized a ‘Fan and Block’ astigmatism wheel which merely screens for the presence of astigmatism. The fan-and-block technique is less utilized in practice nowadays[19] because it is less sensitive at determining small cylinders and a person with a head tilt will not give accurate results. Thus, this test was found to not be sensitive for detecting small cylinders with both apps have been passing those users as not having any astigmatism when there was a possibility of them having small degree of astigmatism.

The detection and correction of even small amounts of astigmatism is important as it is a condition in which the eye does not focus images appropriately, however it may not always result in a significant decrease in vision unlike in the case of spherical refractive errors. For this reason, it may prevent a person from considering or seeking an eye test. Yet, in addition to blurred vision, other debilitating symptoms such as eye stress or strain, squinting, poor night vision, eye irritation, headaches, fatigue and difficulty focusing while reading may occur with astigmatism[20]. Furthermore, astigmatism is reported as having a major effect on the common daily task of night driving with problems like glare from the headlights of oncoming cars or halos around streetlights being attributed to some degree of uncorrected astigmatism[21]. The implication of this can be on the confidence of individuals when engaging in night driving and subsequently on road safety impacting themselves and other road users. Hence, while it is not necessary that screening apps be able to quantify accurately the amount of astigmatism, it is valuable for these screening tests to be able to at minimum, detect the presence of astigmatism so that necessary interventions are made.

For the right eyes, the Paid Astig App showed good sensitivity (98%) but fair specificity (70%) implying that while it may have been able to correctly detect those that had astigmatism, it was not as good in correctly identifying those that did not have astigmatism. In the left eyes, the Free Astig App showed a high sensitivity result indicating this test maybe useful in identifying astigmatism. As no other study was found that assessed the screening for astigmatism using smartphone apps or any other method other than clinical testing, no further comparisons can be made.

In the study there were certain limitations that could have potentially affected the outcome of the results of the study. Convenience sampling was used to select the 313 participants in this study. This sampling method creates various biases including a gender bias towards females in the current study. The findings from this study only hold true for the two apps tested on the iPhone 6 plus and may not be generalized to all iPhone. Different smartphone apps displayed their results in different notations which thus required the researcher to find methods to convert the results into one notation that was the easiest to interpret and draw comparisons. The Optotype sizes, contrast and testing distances were not consistent between all the apps which could have potentially affected the outcome of the results. The iPhone used was always set to maximum brightness and this might produce a glare effect in some participants and a possible after-image. For the majority of participants in this study this was their first encounter with vision screening apps which could have resulted in them being anxious and second guessing their answers on the app. Dishonesty of participants when completing the standard test or smartphone app could also be considered a limitation.

CONCLUSION

Due to the unprecedented popularity of smartphone vision testing and the potential it has to possibly aid in reducing visual impairment it is essential that all apps utilized are fully investigated. However, from this study finds the need for further development and modification in the selected apps for both the CS and Astigmatism. Both the free and paid CS apps overestimated the results and the astigmatism app testing significantly underestimating the number of participants with astigmatism. Therefore, as a start, in order for all four smartphone apps to be considered for use in vision screenings, developers are required to relook at the tests where proper calibration on contrast,

brightness, design and sizing needs to be further investigated. Even though the use of this technology has become popularized, more insight is required into the reliability of these tests which have the potential for increasing access to vision screening and subsequently seeking eye care timeously, for many.

DISCLOSURE STATEMENT

No competing financial interests exist.

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TABLE AND FIGURES

Table i: Conversion from Log CS to Contrast percentage (The Mars Letter Contrast Sensitivity Test user manual., 2003-2010)

log CS	Contrast	log CS	Contrast	log CS	Contrast	log CS	Contrast	log CS	Contrast	log CS	Contrast
0.04	0.912	0.08	0.832	0.12	0.759	0.16	0.692	0.20	0.631	0.24	0.575
0.28	0.525	0.32	0.479	0.36	0.437	0.40	0.398	0.44	0.363	0.48	0.331
0.52	0.302	0.56	0.275	0.60	0.251	0.64	0.229	0.68	0.209	0.72	0.191
0.76	0.174	0.80	0.158	0.84	0.145	0.88	0.132	0.92	0.120	0.96	0.110
1.00	0.100	1.04	0.091	1.08	0.083	1.12	0.076	1.16	0.069	1.20	0.063
1.24	0.058	1.28	0.052	1.32	0.048	1.36	0.044	1.40	0.040	1.44	0.036
1.48	0.033	1.52	0.030	1.56	0.028	1.60	0.025	1.64	0.023	1.68	0.021
1.72	0.019	1.76	0.017	1.80	0.016	1.84	0.014	1.88	0.013	1.92	0.012

Table ii: Showing the frequency of pass and fail categorization of contrast sensitivity determined with the Pelli-Robson clinical test, Free CS App and Paid CS App.

	RIGHT EYES		**LEFT EYES**	
	PASS (%)	FAIL (%)	PASS (%)	FAIL (%)
Pelli-Robson test	61.9%	38.1%	59.3%	39.8%
Free CS app	69.0%	30.1%	68.1%	31.0%
Paid CS app	85.8%	14.2%	83.2%	15.9%

Table iii: Showing the frequency of pass categorization for CS determined with the Pelli-Robson clinical test, Free CS App and Paid CS App according to gender

	PASS (%)			
	Female		**Male**	
	RE	LE	RE	LE
Pelli-Robson	60.9%	59.4%	63.6%	59.1%
Paid app	69.6%	66.7%	70.5%	70.5%
Free app	82.6%	79.7%	90.9%	88.6%

Table iva. Sensitivity and specificity of the Free App in comparison to standard Pelli-Robson test.

		Pelli-Robson (Gold Std)			
		True Pass		True Fail	
		RE	LE	RE	LE
Free App	Pass	68	66	11	11
	Fail	2	1	32	34
Total		70	67	43	45
		Sensitivity		Specificity	
		74%	76%	97%	99%

Table ivb. Sensitivity and specificity of the Paid App in comparison to standard Pelli-Robson test.

		Pelli-Robson (Gold Std)			
		True Pass		True Fail	
		RE	LE	RE	LE
Paid App	Pass	69	65	28	29
	Fail	1	2	15	16
Total		70	67	43	45
		Sensitivity		Specificity	
		35%	36%	99%	97%

Table V: Showing the frequency of participants with astigmatism and no astigmatism as determined with the JCC test, Free Astig App and Paid Astig App

	RIGHT EYES		LEFT EYES	
	No Astigmatism (%)	Astigmatism (%)	No Astigmatism (%)	Astigmatism (%)
JCC test	46 (40.7%)	67 (59.3%)	43 (38.1%)	69 (61.1%)
Free Astig App	83 (73.5%)	30 (26.5%)	84 (74.3%)	28 (24.8%)
Paid Astig App	65 (57.5%)	48 (42.5%)	68 (60.2%)	44 (38.9%)

Table VI: Showing the frequency of participants with astigmatism and no astigmatism as determined with the JCC test, Free Astig App and Paid Astig App classified according to gender

	NO ASTIGMATISM (%)				ASTIGMATISM (%)			
	Female		Male		Female		Male	
	RE	LE	RE	LE	RE	LE	RE	LE
JCC TEST	43.5%	43.5%	36.4%	29.5%	56.5%	56.5%	63.6%	68.2%
PAID ASTIG	76.8%	75.4%	68.2%	72.7%	23.2%	24.6%	31.8%	25.0%

APP								
FREE ASTIG APP	63.8%	63.8%	47.7%	54.5%	36.2%	36.2%	52.3%	43.2%

Table VIIa. Sensitivity and specificity of the Free App in comparison to standard JCC test.

		JCC test			
		True Pass		**True Fail**	
		RE	**LE**	**RE**	**LE**
Free App	**Pass**	30	28	0	0
	Fail	37	41	39	43
Total		67	69	39	43
		Sensitivity		Specificity	
		undefined	88%	45%	undefined

Table VIIb. Sensitivity and specificity of the Paid App in comparison to standard JCC test.

		JCC test			
		True Pass		**True Fail**	
		RE	**LE**	**RE**	**LE**
Paid App	**Pass**	45	25	20	43
	Fail	1	44	47	0
Total		46	69	67	43
		Sensitivity		Specificity	
		98%	36%	70%	undefined