Article • Validation of the Smartphone-Based Snellen Visual Acuity Chart for Vision Screening

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ABSTRACT

Background: The majority of the visually impaired population lives in rural areas, where, at times, it is difficult to obtain consistent visual acuity (VA) chart luminance levels. Electronic devices, being self-luminous, would help overcome this barrier. The current study identified and validated a smartphone-based Snellen VA chart against the standard ETDRS chart for screening and clinical practice.

Methods: The study was conducted in four phases. Phase I: VA chart apps on the Google Play store were explored, screened, reviewed, and calibrated based on the displayed optotype size. Phase II: photometric analysis of room illuminance and VA chart luminance levels was performed. Phase III: the selected smartphone-based Snellen VA chart app was validated against the standard ETDRS chart. Phase IV: repeatability of both the uncorrected and best-corrected VA was checked with the ETDRS chart and the smartphone-based Snellen VA chart app.

Results: Phase I: The Snellen Chart app was found to display the Snellen optotype size accurately (inaccuracy <0.25mm). Phase II: average illuminance of the room was ~420 lux. The luminance level of the retro-illuminated ETDRS chart and the Android smartphone screen was ~180 cd/m^2 and ~200 cd/m^2, respectively. Phase III: there were no statistically significant differences between the ETDRS chart and the Snellen Chart app for uncorrected (median difference: -0.02 logMAR, p=0.39) and best-corrected (median difference: 0.00 logMAR, p=0.94) VAs in all participants (n=200; p<0.05). The Snellen Chart app showed good agreement with the ETDRS chart for both uncorrected (limits of agreement: -0.16 to 0.22 logMAR) and best-corrected (limits of agreement: -0.01 to 0.01 logMAR) VAs in all participants. Phase IV: Both the ETDRS chart and the Snellen Chart app were found to have good test-retest repeatability in participants with emmetropia (n=63) and myopia (n=34) with an overall coefficient of repeatability ranging between 0.03 and 0.05 logMAR (p≤0.10).

Conclusions: VAs measured with the smartphone-based Snellen Chart app are reliable and in good agreement with the ETDRS chart. Thus, both VA assessment methods can be used interchangeably.

Keywords: ETDRS chart, smartphone technology, Snellen Chart app, visual acuity

Introduction

It has been reported that around 2.2 billion people are visually impaired globally, out of which approximately 50% of cases are preventable.[1] Preventable visual impairment is dominated by uncorrected refractive error (88.4 million) and cataract (94 million).[1] In terms of regional differences, the prevalence of visual impairment in low- and middle-income regions (Asia and Africa) is estimated to be four times higher than in high-income regions (North America, Australasia, Western Europe, and Asia-Pacific).[1,2] The majority of the visually impaired population lives in the rural areas of low- and middle-income countries, with limited access to proper healthcare, leading to a lack of adequate diagnosis and treatment.[3,4] Unless healthcare services are made more widely accessible, regional demand is expected to remain largely unfulfilled. For example, individuals in rural areas often suffer from refractive blindness resulting from prohibitive travel time and cost for a pair of glasses.

The magnitude of visual impairment can be easily measured by a simple yet very important visual function

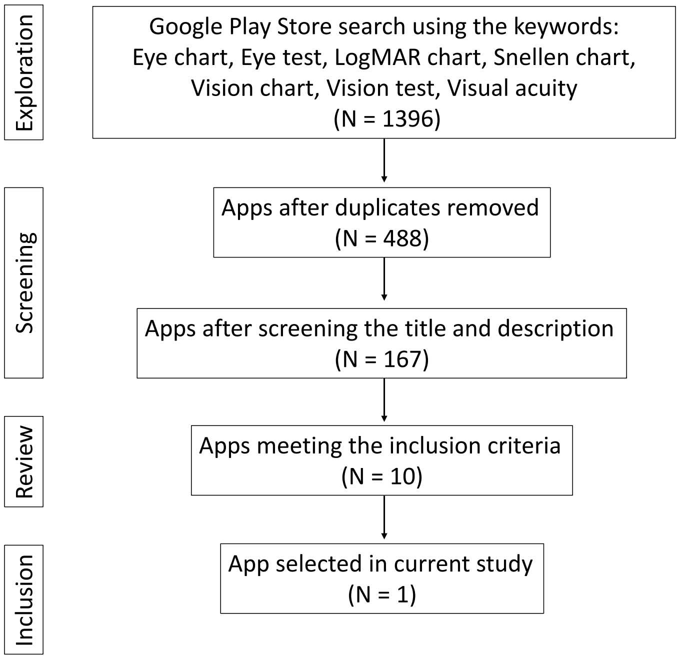

Figure 1. Flowchart summarizing the exploration, screening, and review strategy for identifying the appropriate smartphone-based visual acuity chart

test, the visual acuity (VA). The 6-meter Snellen chart is the most commonly used VA chart in ophthalmic and optometric practice, but it is limited by the non-uniform progression of optotype size, inequality in the number of optotypes on each line, non-uniform spacing between the optotypes and lines, an improper scoring system (for example: 6/6 part), and unequal legibility of the optotypes.[5] These limitations of the Snellen VA chart are overcome by the use of the ETDRS (Early Treatment of Diabetic Retinopathy Study) chart that uses the LogMAR specification.[5] The ETDRS chart is widely used for clinical research since it provides accurate results.[6-8] Nevertheless, the Snellen VA chart remains the dominant method for VA assessment in clinical practice because it is easy to use, smaller in size, is a familiar method, and has better compatibility.[9] Given the varying environmental lighting conditions, it can be difficult to obtain consistent chart luminance levels, impacting the ability to obtain reliable VA.[10-12] In such cases, the electronic VA format, being self-luminous, would help overcome this barrier.

Smartphones in Ophthalmic Practice

Mobile phone technology has evolved rapidly and dramatically. Its use is a growing trend.[13] The use of smartphone technology in modern medical practice is also on a rapid rise.[14] Smartphone technology has enabled volumes of medical literature and reference material to be accessible to students and clinicians in the palm of their hands.[15,16] Medical science is actively adopting mobile technologies for rapid and convenient healthcare delivery, efficient monitoring of the patient, data collection for clinical research, and telemedicine practice, usually in remote areas.[9] With emerging acceptance and application of such technology by medical science and professionals, there is an increasing demand for medical programs, software, and apps to be developed.[9,16] Smartphone use has rapidly expanded, and medical specialties are producing innovative apps relevant to their specialties, such as internal medicine, dermatology, psychiatry, etc. Clinical practice in ophthalmology and optometry[17,18] has also been revolutionized by the development of various apps for easy and effective patient education and clinical assessment of visual functions, such as VA, contrast sensitivity, color vision, refractive error, visual field, etc.[19] The VA measured with the smartphone app, i.e., the Peek Acuity test, was reported to be accurate and repeatable compared with the standard Snellen VA chart and the 5-letter-per-line retro-illuminated ETDRS charts.[9,20-25]

With the majority of the world's visually impaired population living in low- and middle-income countries, the need for effective tools to facilitate early detection and appropriate referral is vital for reducing the prevalence of visual impairment.[26-28] The referral of patients with ophthalmic complaints from primary to specialty care should include a reliable VA measure. In addition, more widespread testing of VA in low- and middle-income countries is likely to lead to greater awareness of preventable and curable eye disease with increased treatment.[29] In such circumstances, an easily accessible, easy-to-use, and reliable vision test in ophthalmic and non-ophthalmic departments could lead to increased accuracy of vision assessment in routine practice.[30,31] Hence, in this study, we identified and validated a smartphone-based Snellen VA chart against the standard ETDRS chart for use in screening and clinical practice.

Materials and Methods

This is a prospective study based on the comparison of the VAs measured using the standard ETDRS chart and the smartphone-based Snellen VA chart on an Android smartphone at a distance of 4 meters. The study was conducted at Sankara College of Optometry (SCO), Sankara Eye Hospital, Bengaluru, India. The participants were the optometry students at SCO. After obtaining approval from the college and hospital authorities in concordance with the tenets of the Declaration of Helsinki, informed consent was

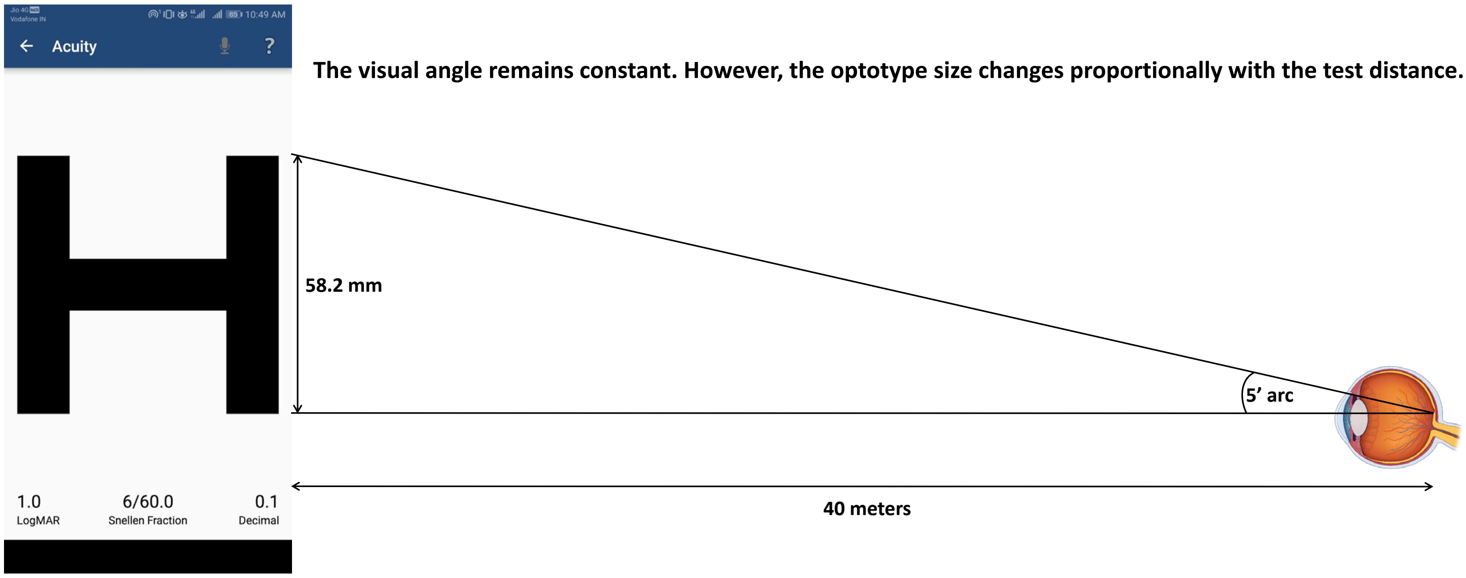

Figure 2. Review and calibration of the smartphone-based Snellen Chart app

obtained from each participant after explaining the nature of the study.

The study was conducted in four phases. Firstly, the available VA chart apps were explored, screened, reviewed, and calibrated on the Android platform, Google Play Store (Figure 1). This was done to identify the most accurate smartphone-based Snellen VA chart app based on the calibration of optotype size (Figure 2). Secondly, the room illumination and VA chart luminance were ensured to be within the normal recommended range. Thirdly, the selected smartphone-based Snellen VA chart app was validated against the standard retro-illuminated ETDRS chart (Figure 3). Fourthly, test-retest repeatability of the VA measures with the ETDRS chart and the smartphone-based Snellen VA chart app was determined.

Phase I – Exploration, screening, review, and calibration of visual acuity applications

The Google Play Store (for Android apps) was searched in January 2017 for VA chart apps using the keywords "eye chart," "eye test," "logMAR chart," "Snellen chart," "vision chart," "vision test," and "visual acuity." This search task was performed by two independent investigators (SKG and DC) on two different Android Operating System (OS) smartphones to ensure that all available apps were identified and discovered. The app search task is summarized in Figure 1. The keyword search identified a total of 1396 apps. The list of apps was checked for duplicates, and these were removed. The apps that included any of the above keywords in their title and description were considered eligible for screening. The apps were then screened for title and description to check eligibility. The apps in languages

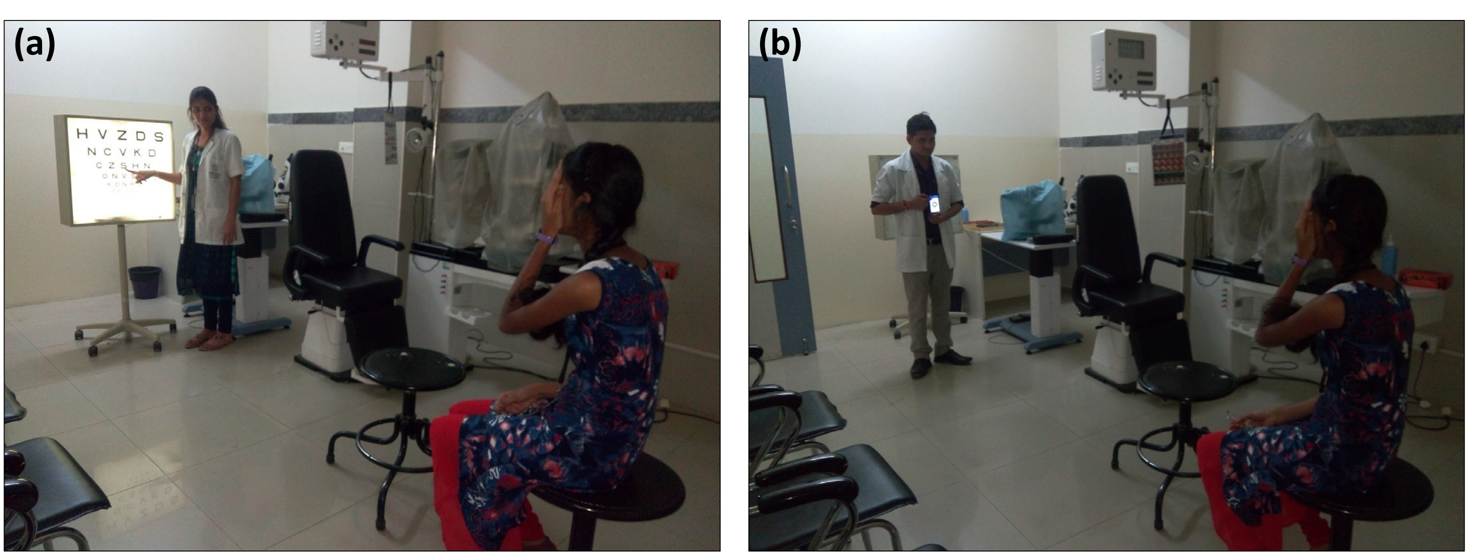

Figure 3. Visual acuity assessment with (a) the standard retro-illuminated ETDRS chart and (b) the smartphone-based Snellen Chart app

Table 1. Characteristics of the Smartphone Applications on the Android Platform (Google Play Store) that were Reviewed for Visual Acuity Assessment

S.N.	Name of the app	Developer (year)	Category	Types of visual acuity chart, optotypes, and other tests	Optotype size details	Test distance	Price (USD)	Website	Reason for inclusion/exclusion
01.	Snellen Chart	Individual (2016)	Medical	Snellen chart: Sloan letters, Tumbling E, Landolt C, LEA symbols, and Numbers Duochrome, Amsler grid, Astigmatic fan	Available	Flexible	Free	https://bit.ly/32cmIic	Included (calibrated optotype size, inaccuracy <0.25 mm, flexible test distance)
02.	Eye Exam	Individual (2014)	Medical	Snellen chart: Serif letters, Landolt C, Tumbling E, Picture chart	Not available	40 cm (fixed)	Free	https://bit.ly/3Fbaghd	Excluded (optotype size details not available)
03.	Visual Acuity Test	Company (2013)	Health & Fitness	Snellen chart: Sloan letters, Landolt C, Tumbling E, Picture chart, and Numbers Duochrome, Astigmatism test	Not available	40 cm (fixed)	Free	https://bit.ly/3yE2D0f	Excluded (optotype size details not available)
04.	Eye Test	Company (2012)	Health & Fitness	Visual acuity (non-Sloan letters and numbers), Color vision, Color Cube (Game), Amsler grid, AMD test, Glaucoma survey, Written test, Contrast sensitivity, Landolt C/Tumbling E, Astigmatism test, Duochrome test, OKN Strip test, Red Desaturation test	Available	30 cm (fixed)	In app purchase	https://bit.ly/3IYVxbE	Excluded (non-Sloan optotypes)
05.	Smart Optometry - Eye Tests for Professionals	Company (2016)	Medical	Visual acuity (non-Sloan letters), Visual acuity + (Tumbling E, Landolt C), Color Vision, Contrast sensitivity, Worth Four Dot test, Schober test, OKN Stripes, Fluorescein light, Red desaturation test, Hirschberg test, Accommodation test, Duochrome test, Aniseikonia test, Amsler grid, MEM Retinoscopy, Maze (Amblyopia test)	Available	40 cm (fixed)	Free	https://bit.ly/3J3PN07	Excluded (non-Sloan optotypes)
06.	Peek Acuity	Company (2016)	Medical	Snellen chart: Tumbling E	Available	2m or 3m (fixed)	Free	https://bit.ly/3sd7yUZ	Excluded (non-Sloan optotypes)
07.	Visual Acuity Test	Company (2010)	Health & Fitness	Snellen chart: Landolt C chart	Available	0.5m, 1m, 3m, or 5m (fixed)	Free	https://bit.ly/3J0zzoE	Excluded (non-Sloan optotypes)
08.	Eye exam Pro	Individual (2014)	Medical	Snellen chart: Serif letters, Landolt C, Tumbling E, Picture chart	Not available	40 cm (fixed)	$2.42	https://bit.ly/32eUDXq	Excluded (optotype size details not available)
09.	EyeQue PVT: Smartphone Vision Test	Company (2017)	Health & Fitness	Requires the EyeQue Personal Vision Tracker (PVT) device to take vision tests	Not available	Not available	$79.00 (PVT)	https://bit.ly/3E2Nxm5	Excluded (optotype size and test distance details not available)
10.	Eye Test Charts	Individual (2015)	Health & Fitness	Reduced Snellen chart: Serif letters, Landolt C Color vision, Dietary tips	Not available	40 cm (fixed)	Free	https://bit.ly/3e6s9lo	Excluded (optotype size details not available, non-Sloan optotypes)

other than English were excluded. If a developer had numerous similar types of apps with different names, only one relevant app was chosen. The apps developed for a purpose other than visual acuity assessment (such as games, amblyopia therapy, eye exercises, etc.) were excluded. Finally, the apps that were developed and received updates between January 2010 and January 2017 were included for review. The apps were then reviewed for the available VA chart, types of optotypes and size details, other screening tests, and preferred test distance. The name, developer, year of release, category, cost, and reason for inclusion/exclusion of the apps were recorded. The summary of the reviewed apps is shown in Table 1.

For the app equipped with optotype (Sloan letter) size details and included in the current study for VA assessment, the accuracy of the displayed optotype was determined. This was done by measuring the actual optotype size displayed on the smartphone screen with a ruler and then comparing it with the intended linear height of an optotype for a specified test distance. A standard Snellen VA chart is designed such that each line would theoretically subtend an angle of 5 min of arc at the distance specified for that specific line. The inverse tangent equation was used to estimate the angle of subtense (5 min of arc) and to determine the linear height (for instance, 58.2 mm for 4/40 (equivalent to 6/60) optotype line (Figure 2)).

Phase II – Room illuminance and visual acuity chart luminance

A digital lux meter (LX1330B, Walfront, Shenzhen, China) was used to measure room illuminance (recommended range: 400-600 lux[12]). Similarly, a luminance meter (LS-110, Konica Minolta, Japan) was used at 4 meters to measure the luminance level of the ETDRS chart and the Android device screen (recommended range: 85-300 cd/m^2).[5]

Phase III – Validation of smartphone-based Snellen visual acuity chart app

The participants who met the criteria for inclusion (distance VA better than 1.0 logMAR) and were willing to participate were enrolled in the study. The study involved two independent examiners who measured VAs on each participant in the same room at different times during the same day to minimize examiner bias. Examiner 1 (DC) measured distance VAs with a 4-meter Original Series ETDRS Chart "R" (Precision Vision, Illinois, USA) fitted into the ETDRS illuminator cabinet (Cat. No. 2425Ev3) (Figure 3a). The given ETDRS illuminator cabinet was set up with two fluorescent lamps, each lamp incorporating a fenestrated sleeve (diffuser) to control the light level for very uniform illumination across the chart. Examiner 2 (SKG) measured distance VAs with a smartphone-based Snellen VA chart on an Android smartphone (Coolpad Note 3, Coolpad Group Limited, Shenzhen, China) at 4 meters (Figure 3b). A printed reduced Snellen near vision chart with numbers (Near vision Chart Book, Aabha Enterprises, India) was used by both examiners to record near visual acuity. Monocular uncorrected VA (UCVA) was recorded for both distance and near. If distance uncorrected VA (UCVA) was worse than 0.00 logMAR, objective refraction was performed using a streak retinoscope (Heine Beta 200, Gilching, Munich, Germany), followed by subjective refraction, and monocular best-corrected VA (BCVA) was recorded for both distance and near.

Each participant was asked to read every optotype in a line from top to bottom to a point (endpoint) where he/she was not able to recognize the optotype or misidentified the optotype twice or more. Here the VA assessment was terminated, and measurements were recorded by using the letter-by-letter method. Each optotype has a score value of 0.02 log units. Since there are 5 optotypes per line, the total score for a line on the ETDRS chart represents a change of 0.1 log units.[5] The logMAR VA score was calculated by using the following formula:

logMAR VA = logMAR value of the best line read + 0.02 × (number of optotypes missed)

In the smartphone-based Snellen VA chart, one optotype was displayed at a time on the screen. A total of five optotypes were displayed. Once the participant responded to a displayed optotype, the next optotype was displayed, and so on, until the endpoint was achieved as described above for the ETDRS chart. The letter-by-letter method was applied here as well to calculate the logMAR VA score by using the above-mentioned formula (for ETDRS chart).

Phase IV – Test-retest repeatability

Test-retest repeatability (inter-session) was performed on a separate day for both the ETDRS chart and the smartphone-based Snellen VA chart. A subset of participants from Phase III underwent assessment of BCVA with their spectacle correction, if appropriate.

Statistical analysis

VA was the outcome measure in the current study. The smartphone-based Snellen VA chart reported the VA score in three formats: logMAR notation, Snellen fraction, and decimal units. However, only the logMAR VA score was recorded for analysis. The data input and

Table 2. Mean ± Standard Deviation (SD) of Age and Spherical Equivalent Refraction (SER); Median (minimum to maximum), Median Difference with Limits of Agreement (LOA) for Uncorrected and Best-Corrected LogMAR Visual Acuities with the Standard ETDRS Chart and the Snellen Chart App in Different Refractive State

Participants	Mean ± SD age (years)	Mean ± SD SER (D)	Visual acuity	Visual acuity charts	Median (min to max) logMAR visual acuity	Hodges-Lehmann median difference	95% CI of median difference	95% CI of LOA (logMAR visual acuity)	p-value
All (n = 200)	21.23 ± 3.09	-0.58 ± 1.28	Uncorrected	ETDRS chart	0.00 (-0.32 to 1.00)	-0.02	-0.03 to -0.01	-0.16 to 0.22	0.39
				Snellen Chart app	0.00 (-0.36 to 1.00)				
			Best-corrected	ETDRS chart	-0.10 (-0.32 to 0.10)	0.00	0.00 to 0.00	-0.01 to 0.01	0.94
				Snellen Chart app	-0.10 (-0.30 to 0.10)				
Emmetropia (n = 126)	21.00 ± 2.72	-0.03 ± 0.14	Uncorrected	ETDRS chart	-0.08 (-0.32 to 0.40)	-0.03	-0.04 to -0.02	-0.14 to 0.21	0.06
				Snellen Chart app	-0.10 (-0.36 to 0.40)				
			Best-corrected	ETDRS chart	-0.10 (-0.32 to 0.10)	0.00	0.00 to 0.00	-0.012 to 0.014	0.92
				Snellen Chart app	-0.10 (-0.30 to 0.10)				
Myopia (n = 68)	22.00 ± 3.39	-1.72 ± 1.66	Uncorrected	ETDRS chart	0.49 (0.00 to 1.00)	-0.01	-0.04 to 0.00	-0.20 to 0.25	0.67
				Snellen Chart app	0.41 (-0.20 to 1.00)				
			Best-corrected	ETDRS chart	-0.05 (-0.30 to 0.10)	0.00	0.00 to 0.00	-0.004 to 0.004	0.99
				Snellen Chart app	-0.05 (-0.30 to 0.10)				
Hyperopia (n = 6)	23.00 ± 4.71	+0.73 ± 0.18	Uncorrected	ETDRS chart	0.20 (-0.20 to 0.32)	0.00	-0.02 to 0.10	-0.10 to 0.07	Cannot estimate p-value (small sample size)
				Snellen Chart app	0.25 (-0.20 to 0.30)				
			Best-corrected	ETDRS chart	-0.09 (-0.30 to 0.00)	0.00	0.00 to 0.00	0.00 to 0.00	
				Snellen Chart app	-0.09 (-0.30 to 0.00)				

statistical analysis were done by using the MedCalc Statistical Software version 20.019 (MedCalc Software Ltd, Ostend, Belgium; https://www.medcalc.org; 2021). The Shapiro-Wilk's test was used to determine whether the data was normally distributed. Based on the normality of the data, a parametric (paired t-test) or non-parametric (Wilcoxon signed rank test) test was performed. VA measurements were compared between the ETDRS chart and the Snellen Chart app using Bland-Altman analysis. A p-value <0.05 was considered to be statistically significant.

Results

Phase I

A total of ten smartphone-based VA apps were reviewed after fulfillment of inclusion and exclusion criteria. Of those apps, the Snellen Chart (v2.5.5) was found to be appropriate for this study because the actual optotype (Sloan letters) size in the Snellen Chart app exactly matched the intended Snellen optotype size for all lines (inaccuracy: <0.25 mm, Table 1) at a test distance of 4 meters. The Snellen Chart app had a single or line option to select the optotype display mode in the settings menu. When opting for the single optotype display mode in the current study, it was found that the Snellen Chart app displayed only one optotype at a time; hence, it did not exhibit the progression of optotypes like the ETDRS chart. Screen brightness and contrast were set at the highest available level for all measurements. Other options in the Snellen Chart app were set to default settings.

While reviewing the Snellen Chart app on two Android OS smartphones, the Micromax Canvas Fire 4 A107 (Micromax Informatics Ltd., Haryana, India) and the Coolpad Note 3 (Coolpad Group Limited, Shenzhen, China), it was found that the Micromax Canvas Fire 4 A107 (4.5″ screen size) did not project the 1.0 logMAR optotype at the 4-meter distance. On the other hand, the Coolpad Note 3, when held in portrait mode, was able to project it because of its larger screen size (5.5″). Hence, the Coolpad Note 3 smartphone was used in the current study. This Android smartphone had an IPS (In-Plane Switching), HD (High Definition), LCD (Liquid Crystal Display) screen with a resolution of 1280x720 pixels.

Phase II

The average of three measurements taken at each of five locations in the room (center of four walls and center of the room) at eye level while sitting on the examination chair (~0.50 – 0.75 meters from the floor) was considered. The average illuminance of the room was ~420 lux. The newly purchased retro-illuminated ETDRS illuminator cabinet maintained an average luminance level of ~180 cd/m^2 at a distance of 4 meters. Similarly, the average background luminance level of the newly purchased Coolpad Note 3 Android smartphone screen was ~200 cd/m^2 at a distance of 4 meters.

Phase III

A total of 200 participants (92 males and 108 females) aged between 17 and 30 years was recruited for the study. The mean ± standard deviation (SD) age of all participants was 21.23 ± 3.09 years. Wilcoxon signed rank test reported no statistically significant differences in the overall UCVA (p=0.39) and BCVA (p=0.94) between the ETDRS chart and the Snellen Chart app (Table 2).

The participants were further classified based on their spherical equivalent refraction (SER, defined as spherical power plus one-half of cylindrical power) into emmetropia (SER within ± 0.50 D, n=126), myopia (SER ≤-0.50 D, n=68), or hyperopia (SER ≥+0.50 D, n=6). The mean ± SD age and SER for participants with different refractive states are reported in Table 2. For participants with emmetropia and myopia, Wilcoxon signed rank test reported no statistically significant differences in the UCVA and BCVA between the ETDRS chart and the Snellen Chart app (overall p ≥0.06, Table 2). Wilcoxon signed rank test could not estimate the p-value for participants with hyperopia due to the small sample size (n=6).

Bland-Altman plots for limits of agreement in UCVA (Figure 4a) and BCVA (Figure 4b) between the ETDRS chart and the Snellen Chart app is shown for all participants in Figure 4. The Snellen Chart app showed good agreement with the ETDRS chart for both UCVA and BCVA. The mean difference in the UCVA between the ETDRS chart and the Snellen Chart app was reported to be 0.03 logMAR (approximately 2 letters), with a 95% confidence interval (CI) for this difference also being up to 2 letters (95% CI: 0.02 to 0.04 logMAR). Similarly, for BCVA, the mean difference between the ETDRS chart and the Snellen Chart app was found to be 0.001 logMAR (approximately 1 letter) with a 95% CI for this difference also being up to 1 letter (95% CI: -0.001 to 0.001 logMAR).

Phase IV

For test-retest repeatability of VA measurements with the ETDRS chart and the Snellen Chart app, a

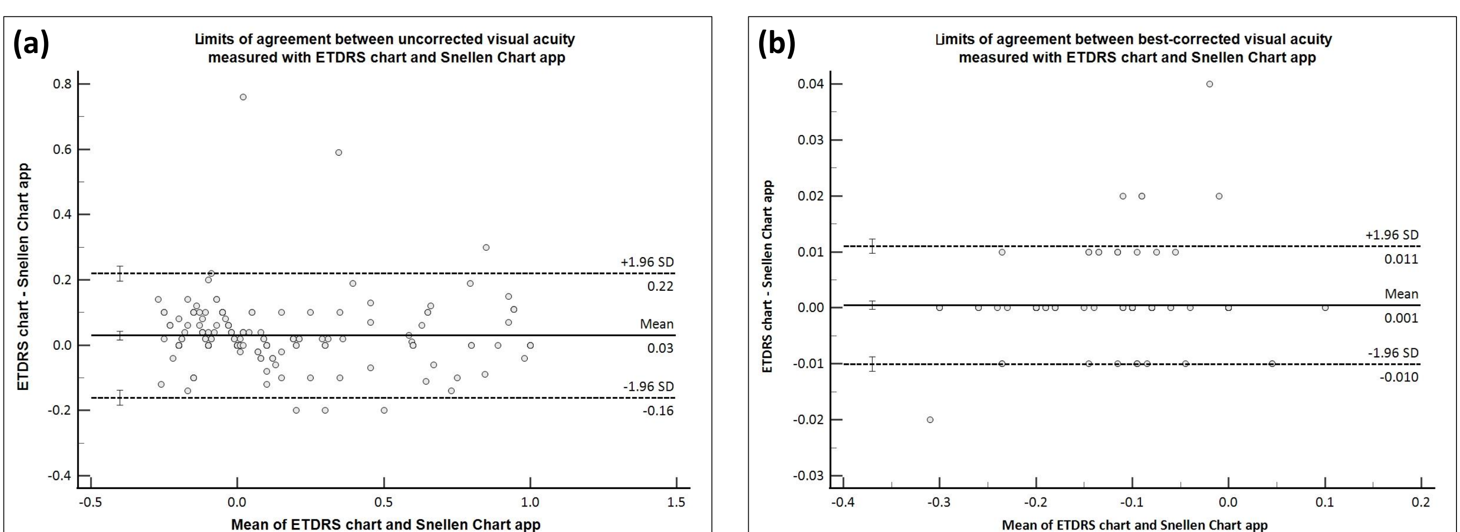

Figure 4. Bland-Altman plots for limits of agreement between the standard ETDRS chart and the Snellen Chart app for (a) uncorrected visual acuity (UCVA) and (b) best-corrected visual acuity (BCVA) measurements

Table 3. Mean Difference ± Standard Deviation (SD) along with Limits of Agreement (LOA) and Coefficient of Repeatability (COR) of Best-Corrected LogMAR Visual Acuities Measured on Two Different Days with the Standard ETDRS Chart and the Snellen Chart App in Participants with Emmetropia and Myopia

Refractive state	Visual acuity charts	Mean difference ±SD (logMAR VA)	95% CI of mean difference	95% CI of LOA (logMAR VA)	COR (logMAR VA)	p-value
Emmetropia (n = 63)	ETDRS chart	-0.04 ± 0.01	-0.04 to 0.02	-0.03 to 0.03	0.04	0.38
	Snellen Chart app	-0.03 ± 0.01	-0.05 to 0.01	-0.03 to 0.03	0.05	0.65
Myopia (n = 34)	ETDRS chart	-0.01 ± 0.06	-0.02 to 0.00	-0.01 to 0.01	0.03	0.62
	Snellen Chart app	-0.01 ± 0.06	-0.02 to 0.02	-0.01 to 0.01	0.04	0.10

total of 97 participants from phase III were enrolled for BCVA assessment with their spectacle correction, if any. Of the 97, 63 were emmetropes (50% of the total 126 emmetropes), and 34 were myopes (50% of the total 68 myopes). Participants with hyperopia were not enrolled due to the small sample size (n=6).

Table 3 shows the mean difference ± SD (paired t-test) along with the limits of agreement (LOA) and coefficient of repeatability (COR) of BCVA measurements with the ETDRS chart and the Snellen Chart app in participants with emmetropia and myopia. Narrower LOA and smaller COR indicate the repeatability to be better.[32] In the current study, BCVA was repeatable within 2 letters (COR=0.04 logMAR) with the ETDRS chart and within approximately 3 letters (COR=0.05 logMAR) with the Snellen Chart app in participants with emmetropia (Table 3). Similarly, in participants with myopia, BCVA was repeatable within approximately 2 letters (COR=0.03 logMAR) with the ETDRS chart and within 2 letters (COR=0.04 logMAR) with the Snellen Chart app (Table 3).

Discussion

In the current study, we identified and validated a smartphone-based Snellen VA chart against the standard ETDRS chart. The study reported that there were no statistically significant differences between the ETDRS chart and the smartphone-based Snellen Chart app for either UCVA or BCVA measurements in all participants including emmetropes and myopes. In addition, the Snellen Chart app demonstrated good agreement with the ETDRS chart for both UCVA and BCVA. When checked for test-retest variability, both the ETDRS chart and the Snellen Chart app were found to have good repeatability (less than one line) in participants with emmetropia and myopia.

From Phase I of the current study, we found that although there are more than 1000 relevant apps in the Google Play Store, the majority lack the strict guidelines governing the design of clinical apps and haven't been tested for repeatability or reliability against a validated reference standard.[16,33,34] Poor mobile health app performance may lead to adverse consequences, such as generating unreliable and inappropriate clinical data and information.[35,36] The United States Food and Drug Administration has formulated a set of policies for device software functions and mobile medical applications, with the goal of developing rigorous guidelines while developing a medical app.[37,38] Given the growth of mobile technology in modern medical practice,[39] all apps designed for clinical decision-making must be thoroughly inspected, calibrated, and validated before they are widely accepted into clinical practice.

Earlier studies using iOS (iPad, iPhone, iPod, etc.) for measuring VA found that the results were reliable and comparable with the standard VA chart measured in clinic settings.[40-43] However, these are expensive for low- and middle-income countries and out of reach to the general population.[44-46] The Android Operating System is reported to be more popular than iOS and Windows Phone.[47] The smartphone based on an Android OS is the most commonly used type of smartphone, not only in developing countries but also worldwide.[48] Hence, in the current study, a cost-effective smartphone with an Android OS was used.

The smartphone-based Snellen Chart app used in the current study was developed by a Portuguese biomedical engineer, João Meneses, in 2016 to provide and to empower regular mobile users and healthcare professionals with a tool with which they could measure VA, based on a classical Snellen VA chart test. This mHealth app was developed for an Android OS and is currently available for free in the Google Play Store. We used this app in the current study because it has the useful feature of swipe gestures to navigate from optotype to optotype (horizontal swipe for optotype randomization within the same line and vertical swipe to change the optotype line). This app is capable of adapting the VA test to different screen sizes, screen resolutions, and testing distances. The app also provides an option to choose the input unit system (metric or imperial) and the Snellen fraction denominator (6/6 or 20/20 format). The screen size, resolution, and contrast can also be set as per the requirement of the examiner and patient. In addition, the app also allows the examiner to select the type of optotype (Snellen letters, Tumbling E, Landolt C, Children symbols, Sloan letters, and Numbers) to be presented in either single or line optotype display mode. The Snellen Chart app also displays VA in all three formats: logMAR notation, Snellen fraction, and decimal units (Figure 2). Furthermore, the app system allows for the randomization of optotypes, which facilitates accurate testing and retesting by minimizing chart learning. The app received a recent update in November 2022 (v3.1.2) with a few additional tests, such as Duochrome, Amsler grid, and Astigmatic fan.

There are several other viable smartphone-based VA apps on the Google Play Store (such as Visual Acuity Charts, Eye Chart for Eye Care Professionals, REST Rapid Eye Screening Test, OcularCheck: Acuity Exam, EyeCharts – Visual Acuity, Snellen Chart, OptoCharts – All eye tests, Tumbling E Chart, etc.), which were developed after 2017 (after the current study was conducted). When grossly screened, these apps appear to be good enough for VA assessment. However, validation studies are required before adapting them clinically.

Phase II of the current study discusses that smartphones are, on the whole, more expensive than a basic printed Snellen VA chart but less expensive than a retro-illuminated ETDRS or Snellen chart.[49] Due to the size, weight, and power requirements, it is not easy to operate retro-illuminated ETDRS or Snellen VA tests in outreach eye health camps.[50,51] At times, it is also difficult to obtain consistent chart luminance levels; electronic devices, being self-luminous, would overcome this barrier. Also, the conventional Snellen or ETDRS chart may get worn off and turn yellowish because of the extensive use and mishandling of these charts, due to which the color and contrast of the charts may degrade over time. This potentially affects the accuracy of VA measurement. In contrast, smartphones are portable and lightweight, with easy access to VA apps. Also, the smartphone's inbuilt screen brightness and contrast remain stable for a longer time. Hence, the accuracy of the VA measurements can be maintained. However, the actual letter luminance and contrast measurement were out of the scope of this study.

Modern smartphones and tablets have glossy screens, which cause reflections due to bright sunlight outdoors. This may lead to glare formation and result in poor VA measurement. Previously, the glare was eliminated by using an antiglare screen over the screen of the tablet being used.[52] In addition, it has been suggested that the source of light and charts should be installed in such a way that the effects of glare and reflections are minimal.[53] Particularly in the case of projected charts, the degradation of contrast by ambient light should be avoided or at least minimized.[54] In the current study, the ETDRS chart and the smartphone-based Snellen Chart were oriented perpendicular to the floor, and they were also positioned facing away from overhead light sources to prevent the screen contrast and optotypes from being detrimentally affected by glare (Figure 3). Thus, a screen guard or anti-reflection screen was not required in our study. A broadband anti-reflective surface has been recently fabricated with a moth-eye-like structure for sunlight-readable flexible display applications.[55] This proposed nanostructure offers excellent optical properties, such as low luminous reflectance (~0.23%), high transmittance (>95%), and low haze (<1%). This could be the future of innovative anti-reflective films, and its application in modern smartphones may help to get rid of screen glare.

The results of Phase III of the current study were obtained from the Bland-Altman analysis. Given that the VA data were not normally distributed, the Bland-Altman analysis (LOA and COR) may not technically be valid, but we proceeded with the Bland-Altman analysis anyway for comparison to prior works. The results of the current study are consistent with the previous studies where the Peek Acuity smartphone test[9,20-25,56-59] was reported to be accurate and repeatable compared to the VA measured using the 5-letter-per-line retro-illuminated ETDRS chart, the conventional Snellen VA chart, and the COMPlog distance VA chart. Previous results also indicated that the smartphone-based VA tests agreed well with those of the ETDRS and Snellen VA charts.[10,21-26,56-59] In addition, previous studies report that smartphone-based VA apps can also be used for measuring near VA.[43,45,59]

In the current study, the agreement between the standard ETDRS chart and the smartphone-based Snellen Chart app appears to be better for BCVA than UCVA. However, for VA screening and measurement, particularly in rural areas, UCVA is usually considered a more important metric than BCVA. Hence, further validation studies are indispensable in the interest of the expressed purpose of the study. Good reliability and repeatability of the smartphone-based VA apps would turn modern smartphones into useful vision screening tools to be used in community health programs, especially in rural areas and schools,[21,23,25] without the need for a retro-illuminated ETDRS or Snellen chart.[58]

Phase IV of the current study reported that the test-retest repeatability of BCVA was less than one line with both the ETDRS chart and the Snellen Chart app in emmetropes and myopes. These measures were comparable to earlier studies that included Peek Acuity.[9,60,61] We determined the repeatability of the ETDRS chart and the Snellen Chart app in participants with their refractive correction in place (myopes). This was done considering that the patients visiting an eye hospital would be given the refractive correction for optimum BCVA.

In the COVID-19 pandemic, incorporating the smartphone-based measures of vision assessment was crucial for teleophthalmology because it reduced the patient's expenses and saved travel time.[59] This also ensured an extent of safety to both the examiner and patient. The validated smartphone-based VA charts can also be used for self-monitoring of vision in patients diagnosed with vision-threatening diseases such as diabetic maculopathy, age-related macular degeneration, glaucoma, etc.[62-64] It may help for the easy and early detection of vision change and hence, timely referral. Overall, these apps provide a way to standardize and to improve the efficiency of ophthalmic care.[43]

Limitations of our study include enrolling optometry students of the college rather than the traditional patients who could have demonstrated real-life challenges while using the smartphone-based VA app. For participants with visual impairment, amblyopia, or ocular pathologies, the test-retest repeatability can vary beyond one line.[61] VA also depends upon various other factors, such as type of VA chart used,[65,66] resolution of the displayed screen,[65] participant age (children and elderly giving variable responses),[65,67] optical defocus,[68] ocular abnormalities,[65] and the scoring method used to record the VA.[66] In addition, iOS and Windows Phone devices were not used in this study. Therefore, future validation studies using other smartphone operating systems are required to determine whether other devices could be of similar clinical use.

The manner in which the smartphone was held in the current study could also have been an issue in terms of stability for an extended duration. Over time, orientation of the smartphone can vary, as it can tilt forward, backward, or towards the right or left side. This may hinder and cause potential errors in the VA measurements. The use of a stable stand along with a fixed smartphone holder is necessary to keep the smartphone in the appropriate position and orientation, thereby avoiding potential errors in VA measurement that might arise. Further validation studies evaluating the capability, reliability, accuracy, and effectiveness of the smartphone-based VA apps assessing near VA in addition to distance VA; involving a larger population of different age groups and geographical areas (urban vs rural); and including a wider range of refractive errors (including hyperopia), amblyopia, vision-threatening ocular conditions, and low vision with mild/moderate/severe vision impairment are necessary to establish the potential benefits and challenges of such apps for vision screening, clinical assessment, and teleconsultation in real-life scenarios.

Conclusions

The standardized and validated smartphone-based VA apps are innovative and useful because they transform an old-style, poster-design test into a new, modern, digitalized, intuitive, and ubiquitous test. The VAs measured with the smartphone-based Snellen Chart app are accurate and in good agreement with the standard ETDRS chart, thereby generating reliable VA measurement results. Thus, both of the VA assessment methods can be used interchangeably. The validated smartphone-based VA apps can also be widely used for telemedicine and self-monitoring of vision, as well as in community outreach and school eye healthcare programs. This can aid in the early diagnosis of refractive error and referral of many vision-related disease conditions on time. This may also lead to more people receiving timely and appropriate eye care via efficient evaluation, diagnosis, treatment, and management, helping to control preventable and curable visual impairment.

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