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Visual acuity and contrast sensitivity screening with a new iPad application ☆

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ABSTRACT

We present a new iPad application (app) for a fast assessment of Visual Acuity (VA) and Contrast Sensitivity (CS) whose reliability and agreement was evaluated versus a commercial screening device (Optec 6500). The measurement of VA was programmed in the app in accordance with the Amblyopia Treatment Study protocol. The CS was measured with sinusoidal gratings of four different spatial frequencies: 3, 6, 12 and 18 cpd at the same contrast values of the Functional Acuity Contrast Test (FACT) included in the Optec 6500. Forty-five healthy subjects with monocular corrected visual acuities better than 0.2 logMAR participated in the agreement study. Bland-Altman analyses were performed to assess the agreement and Deming regressions to calculate Mean Differences (MDs) and Limits of Agreement (LoAs). Coefficients of reliability were 0.15 logMAR for our method and 0.17 logMAR for the ETDRS testing protocol. For testing the CS, our test showed no statistically significant differences compared with the FACT at any spatial frequency ($p > 0.05$). The MDs were lower than 0.05 log units for all spatial frequencies.

1. Introduction

Vision screening programs are intended to identify eye problems which occur in children or adults and refer them for further evaluation. Although there is a battery of screening methods designed to detect specific eye disorders, some screening techniques can be considered "multi-purpose," minimizing the need for several individual tests [1]. For instance, visual acuity (VA) is considered an essential part of any eye examination [2] and it is used in the screening of refractive errors [3] and amblyopia [4]. On the other hand, the Contrast Sensitivity Function (CSF) is considered an additional test for specialized clinical evaluation, and has been generally accepted as a better predictor of visual performance than high contrast VA [5–7].

Several tests and methods have been proposed for the assessment of VA and CSF. Nowadays, the Early Treatment of Diabetic Retinopathy Study (ETDRS) testing protocol is generally accepted as the gold standard of VA measurement in adults [8–10]. With regard to contrast sensitivity (CS), although the Pelli-Robson chart is considered the gold standard to compare optotype's based CS tests [11], currently there is not a commercial gold standard test to measure CS by sinusoidal gratings. Despite this fact, some clinical tests have been developed and they represent a good solution in vision screening programs; the most used are the Functional Acuity Contrast Test (FACT) [12,13] and the Vector Vision CSV-1000 [14,15]. Clinical CS tests commonly use 9 patches of sinusoidal gratings with different contrast levels. They could differ in the step sizes, ranges, or the psychophysical method to achieve the threshold [16]. The Optec 6500® is a commercial screening device that complies with the ANSI standard [17] and includes the ETDRS and FACT tests to evaluate VA and CS respectively.

Ever since computer tablets appeared, new applications (apps) have been proposed in the field of visual science [18–21]. The great advantage of using these portable devices is the potential standardization of measurements. This is because many models of tablets have screens with similar characteristics such as chromaticity and resolution. Therefore, it can be hypothesized that if a developer takes into account the technical data of the tablets in the design of an app, any operator who uses the same display in any part of the world will measure the visual function under the same conditions. However, to provide accurate presentation of test stimuli, individual device calibration may be necessary to ensure that any variances between devices, even of the same manufacturer and model, are taken into account. In this respect, in a recent paper Tahir et al. [22] suggested practical means to optimise quality of display for vision testing including screen calibration.

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The assessment of the VA and CS with an iPad has recently been proposed under different approaches: Black et al. [19] implemented a platform for testing distance VA. To evaluate CS, Kollbaum et al. [20] developed an elementary test consisting of two letters on each page of an iBook, having 0.1 log units of difference between pages. This test was compared with the Pelli-Robson and Freiburg VA tests and gave significantly lower values with the first one and good agreement with the second one. On the other hand Dorr et al. [21] implemented *the quick CSF method* proposed Lesmes et al. [23], to evaluate the response to sinusoidal gratings of 16 spatial frequencies log-spaced from 0.42 to 13.7 cycles per degree (cpd). This test was validated with measurements obtained from four normally sighted subjects on specialized laboratory equipment. However, in spite of its name, this method is still rather time-consuming for screening purposes (up to 5 min) [21].

The aim of this study is to introduce a new iPad app designed for a fast screening of VA and CS, which represents an alternative to other expensive and large-format screening instruments. The obtained VA and CS records and test-retest reliabilities are compared with those achieved with the *Optec6500*.

2. Methods

The proposed app was developed with ActionScript 3.0 programming language for mobile devices and then compiled for IOS with Adobe Flash Builder (Adobe Systems, Inc.). The tablet used to perform this research was a third generation iPad with a retina display (2048-by-1536-pixel resolution at 264 pixels per inch). The suitability of this device for visual psychophysics purposes has been previously reported [21,24]. A Spyder4Elite colorimeter was used to measure the chromaticity of the iPad screen at maximum brightness. Data obtained from the colorimeter were used to create the CS stimuli. The room lighting during measurements was controlled with the luminance meter LX1330B Luxmeter. The app consists of two primary components, intended to be useful for a fast screening of VA and CS.

2.1. Fast Screening of Visual Acuity (FSVA)

The assessment of the VA with the proposed app follows the Amblyopia Treatment Study (ATS) testing protocol [25]: The subject has to recognize which of the four letters (HOTV) with 50% crowding bars appear isolated in the centre of the screen, (Fig. 1, left). On each visual acuity level, a black optotype is presented over a white background with a luminance of 342 cd/m^2. The presentation distance was 3 m. The optotype size was automatically fitted for this distance by the application. The psychophysical method to reach the VA threshold was also included in the app, as described by the ATS testing protocol. In this way, the operator task only consists in touching one of the five click buttons at the margin of the screen (corresponding to the HOTV letters plus one button for a null response) according to the answer given by the observer. Even though the ATS protocol consists of a binocular pre-test followed by a monocular screening, the first one was omitted to shorten the task, and it starts directly with monocular screening at 0.8 logMAR. The reinforcement phase described in the ATS protocol was also omitted and the application automatically goes from phase 1 to phase 2. In this way, each VA measurement can be completed in approximately one minute.

2.2. Fast Screening Contrast Sensitivity (FSCS)

For a rapid assessment of the CS we propose the use of sinusoidal gratings of four different spatial frequencies: 3, 6, 12 and 18 cpd. The contrast of the gratings was determined by the luminance difference of the white and dark bars, as described by Pelli in Ref. [26]. The sinusoidal gratings appear in a vertical orientation or tilted ±15° from the vertical and are presented in circular patches with blurred edges that fade the gratings into an achromatic background of mean luminance (85 cd/m^2). The angle subtended by the patchs from the presentation distance was 1°. A total of 9 patches of different contrasts were generated for each spatial frequency and each orientation. Stimuli were programmed with *MATLAB* software (The MathWorks, Natick, MA) and the library *COLORLAB* [27]. The CS values for each frequency and the psychophysical procedure were programmed using the same parameters of the FACT [12,13,28] in order to obtain comparable results (see Table 1). The measurements of the CS thresholds for four spatial frequencies were completed in a mean of two minutes and a half per eye.

2.3. Subjects and procedures

Forty-five subjects, comprised of 21 males (mean age: 36 ± 11 years) and 24 females (mean age: 33 ± 10 years), were recruited from university staff and students at the University of Valencia, Spain. Exclusion criteria included strabismus or any cause of monocular reduced visual acuity worse than 0.2 logMAR with habitual correction (measured with ETDRS). Informed consent was obtained from each subject just before starting the procedures. The research was conducted in accordance with the principles laid down in the Declaration of Helsinki. Approval from the human research ethics committee of the Universitat de València (Spain) was obtained before the study began.

All trials were performed in the same room illumination (15 lx). The same procedure was carried out in all sessions by the same operator and with the patient wearing the habitual correction. VA and CS were measured with the iPad test and, after a short break, with the *Optec6500* using the *day testing* option (85 cd/m^2

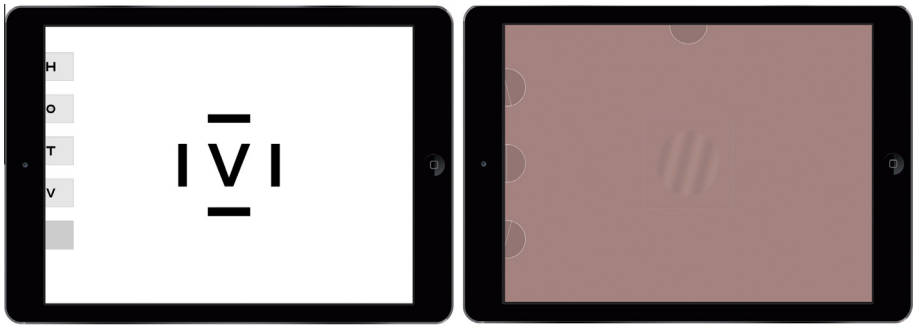

Fig. 1. iPad application patterns. Crowded optotype in the FSVA (left) and sinusoidal grating in the FSCS (right). FSVA: Fast Screening of Visual Acuity, FSCS: Fast Screening Contrast Sensitivity.

Table 1
Contrast sensitivity values (in log units) for the patches of the four spatial frequencies in FSCS application. These values are the same values comprised in the FACT. FSCS: Fast Screening Contrast Sensitivity, FACT: Functional Acuity Contrast Test, cpd: cycles per degree.

Patch	Spatial frequency (cpd)			
	3	6	12	18
9	2.20	2.26	2.08	1.81
8	2.06	2.11	1.93	1.66
7	1.90	1.95	1.78	1.52
6	1.76	1.81	1.63	1.36
5	1.60	1.65	1.48	1.23
4	1.46	1.52	1.34	1.08
3	1.30	1.36	1.18	0.90
2	1.18	1.20	1.04	0.78
1	1.00	1.08	0.90	0.60

target illumination). Twenty-five subjects from the total were cited for two more sessions, spaced a week apart, in order to evaluate the reliability of both devices.

2.4. Statistical analysis

Although both of the subjects' eyes were measured during testing procedures, only one was included in the agreement and reliability analyses after a random selection [29]. VA and CS variables were not normally distributed; therefore non-parametric tests were employed. Statistical significances of VA and CS inter-eyes and inter-test differences were assessed with the Wilcoxon signed-rank test. On the other hand, differences between tests followed an approximately normal distribution, therefore the Bland-Altman analysis [30] was performed to evaluate the agreement between iPad apps and Optec6500 tests and to assess test-retest reliabilities. The *MethComp (version 1.25)* package was used with the *R* statistics software *(version 3.1, R Development Core Team, 2014)* in order to complete the statistical analyses described below.

2.5. Agreement

Differences between measurements for each test were plotted against the average and the 95% limits of agreement (LoAs) were computed depending on whether the average difference and the variability of differences were constant throughout the range of measurement [30]. We checked the hypotheses of constant differences and constant standard deviations by means of a Deming regression (function *DA.reg*) [31]. If the corresponding p values for both hypotheses were significant ($p < 0.05$), conversion equations were employed on the plot, and mean differences (MDs) or LoAs were represented considering linear correlations (function *BA.plot,* parameters *dif.type* = "*lin*", *sd.type* = "*lin*").

2.6. Reproducibility

A Friedman 2-way analysis of variance by ranks with multiple comparisons was used to evaluate differences in medians among the three days [32]. The residual standard deviation (σ_m) with each test was computed with the data from the subjects who completed a total of 3 sessions (replicates). LoAs were estimated again considering models of exchangeable or linked replicates. A random permutation (function *perm.repl*) was done comparing the resulted LoAs with the original data by a Bland-Altman plot in order to apply the exchangeable or linked models proposed by Carstensen et al. [33]. Since the random permutation of replicates had little effect in the LoAs, they were computed as exchangeable. LoAs of test differences were compared with the reproducibility coefficients (r) of each test defined as $1.96 \times \sqrt{2} \times \sigma_m$ (exchangeable replicates) in order to know if test agreement might be related with test reliability (*RepCoef* in function *BA.est*).

3. Results

3.1. Visual acuity

No statistically significant differences were found in the comparison between right and left eyes with both tests, although as it can be seen in Fig. 2, the difference between eyes was higher with ETDRS ($p = 0.09$) than with FSVA ($p = 0.85$) at around 0.1 logMAR. In the comparison between tests (Fig. 3), VA scores obtained with FSVA had better results than those obtained with ETDRS with a MD of 0.06 logMAR ($p < 0.001$). This difference would be approximately three letters on a logMAR chart with five letters per line. The null hypotheses of constant MDs and constant SDs were accepted ($p > 0.05$) which suggest that EDTRS results could easily be predicted with the FSVA along the range of visual acuities measured (−0.2 to 0.2) by simply subtracting MD from FSVA results.

Friedman test showed significant median differences between days χ^2 (2, n = 25) = 12.15, $p = 0.002$ with ETDRS. The median was 0 logMAR for the first day and −0.1 logMAR for the other two days. On the other hand, medians with FSVA were −0.1 logMAR in the three days with no statistically significant differences among days χ^2 (2, n = 25) = 2.61, $p = 0.27$. The number and percentage of subjects that reported differences within 0.1 logMAR in the three days were 24 (96%) with FSVA and 21 (84%) with ETDRS. The permutation indicated that replicates should be treated as exchangeable, therefore a recalculation of LoAs was performed under this condition obtaining a value of ±0.2 logMAR, similar to that reported in the agreement study (Fig. 3). Coefficients of reliability (r) were 0.15 logMAR for FSVA and 0.17 logMAR for ETDRS.

3.2. Contrast sensitivity

The analyses of median differences between right and left eyes were not significant for all spatial frequencies and with both tests ($p > 0.05$). There was a ceiling effect for spatial frequencies of 3 and 6 cpd which was manifested by a negative skewed distribution in the box plot diagrams (see Fig. 4). Even though the differences between the distributions of FSCS and FACT increase with the increment of the spatial frequency, no statistically significant differences were found at any spatial frequency ($p > 0.05$).

MDs were below 0.05 log units for all spatial frequencies and LoAs were increased with the spatial frequency (see Fig. 5). Deming

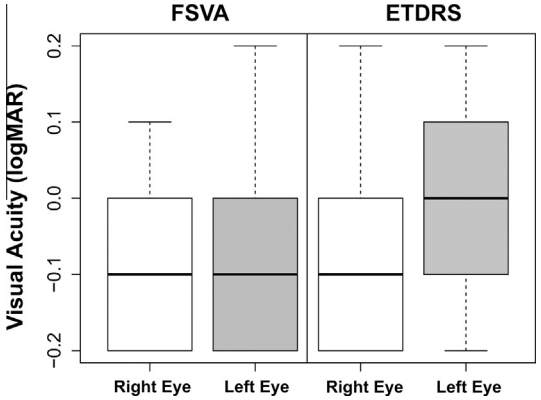

Fig. 2. Box plot diagrams showing visual acuities from right and left eyes measured with both visual acuity tests. FSVA: Fast Screening of Visual Acuity, ETDRS: Early Treatment of Diabetic Retinopathy Study, logMAR: logarithm of the minimum angle of resolution.

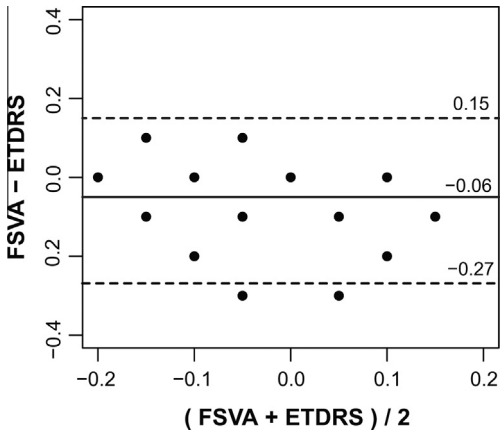

Fig. 3. Bland–Altman plot showing the mean difference against the average of FSVA and ETDRS (solid line), limits of agreement are also represented by dashed lines. FSVA: Fast Screening of Visual Acuity, ETDRS: Early Treatment of Diabetic Retinopathy Study.

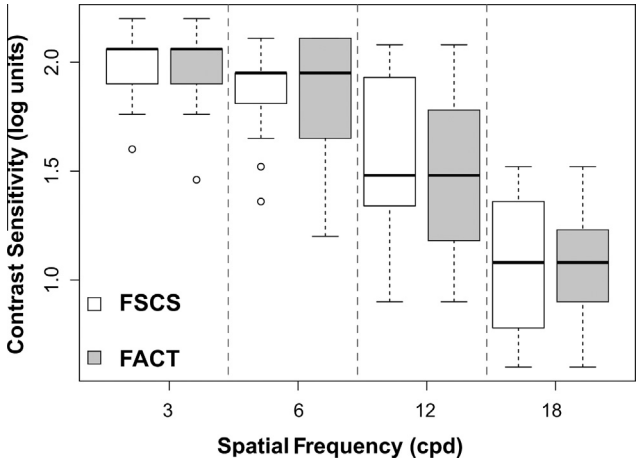

Fig. 4. Box plot diagrams showing the contrast sensitivities obtained with FSCS and FACT for spatial frequencies of 3, 6, 12 and 18 cpd. The boxes indicate the first and third quartiles, the dark horizontal lines represent the median, and the extreme horizontal lines are the minimum and maximum. Other points represent outliers. FSCS: Fast Screening Contrast Sensitivity, FACT: Functional Acuity Contrast Test, cpd: cycles per degree.

regression showed that although there were constant MDs for all the spatial frequencies ($p > 0.05$), constant SDs could not be assumed for 3, 6 and 18 cpd ($p < 0.05$). Therefore LoAs for non-constant SDs were also represented on Bland-Altman plots with the corresponding equations to compute the LoAs along the average of test measurements (a).

Table 2 shows that even though no statistical significant differences were found in the Friedman analysis of variance of the three days, a low reproducibility was obtained with both tests, but this was slightly better with the FACT. Considering step sizes between patches around 0.15 log units, reproducibility coefficients (r) from Table 2 correspond to a maximum difference of 2, 3, 4 and 4 patches for 3, 6, 12 and 18 cpd, respectively, with FSCS. Reproducibility slightly improved to 2 patches for 3, 6, and 12 cpd while a maximum difference of 3 patches was obtained for 18 cpd with FACT. The r was very close to the LoAs; therefore, the lack of agreement between FSCS and FACT can be attributed to the low reliability of both tests.

4. Discussion

4.1. Visual acuity

We found statistically significant differences between the records of VA obtained with FSVA and ETDRS, resulting in a better VA of 0.06 logMAR with our test. This result is coincident with the outcomes reported by Rice et al. [34] who found an MD of 0.06 logMAR between ATS and ETDRS. Leone et al. [35] also found a better VA with the ATS procedure than with HOTV and ETDRS charts even though the latter ones incorporated a staircase method that improves the VA results. Therefore, the apparent lack of agreement between tests in our study can be attributed to the differences in the VA protocols rather than to the use of different instruments. It is also important to note that even though non-statistically significant differences were found between eyes with both tests, lower differences were manifested with FSVA. In regards to test reliabilities, we obtained a better coefficient of reproducibility with FSVA than with ETDRS. 96% of subjects reported differences within 0.1 logMAR with the FSVA, this percentage is consistent with the 93% previously reported with ATS protocol [25]. It is important to note that, even though we applied little modifications to the ATS in order to reduce time of testing (such as skipping the reinforcement phase), reliability has not been reduced.

Unlike a previous work carried out with another VA test for iPad [19], we did not have glare problems. Given that our study was conducted preventing reflections over the screen, there is a possibility that dissimilar results would have arisen if the VA had been measured in a high light environment with reflections over the screen. One limitation of our methodology might be that the brightness of the screen was set on the maximum level (342 cd/m^2), which is over the recommended background luminance [36]. We decided to perform the study in this way to ensure that all evaluations were conducted under the same lighting conditions. Future work will concentrate on developing a system to measure environmental illumination and automatically set up the background luminance in accordance to the measured value.

4.2. Contrast sensitivity

Dorr et al. [21] have recently demonstrated that the CSF assessment on a mobile device may be indistinguishable from that obtained with specialized laboratory equipment. Although they implemented the quick CSF method [23] that reduces the testing time to no more than 5 min, this method could still be very time-consuming for screening procedures. Thus our proposal is a valuable alternative since it can be completed in half the time. The FSCS results demonstrated a good agreement with FACT with no statistically significant differences between tests at any spatial frequency. Specifically, the MDs were lower than 0.05 log units for all spatial frequencies. In a previous work, Franco et al. [15] compared the agreement between VCTS-6500 and CSV-1000. They found statistically significant differences with MDs of 0.3, 0.08, 0.2 and 0.18 log units for 3, 6, 12 and 18 cpd respectively. These differences can be attributed to the fact that these tests employ different step sizes between CS levels.

In our case, we found a lower agreement between tests at high spatial frequencies, but this fact could be related to test-retest reliabilities of FSCS and FACT. In fact, even though this issue was not mentioned in their discussion, Pesudovs et al. [16] also found similar test-retest reliabilities, being poorer (as in the present study) with the increment of the spatial frequency. The dependency of reliability with the CS level was also reported by Kollbaum et al. [20] although they used optotypes which contain a wide range of spatial frequencies instead of sinusoidal gratings.

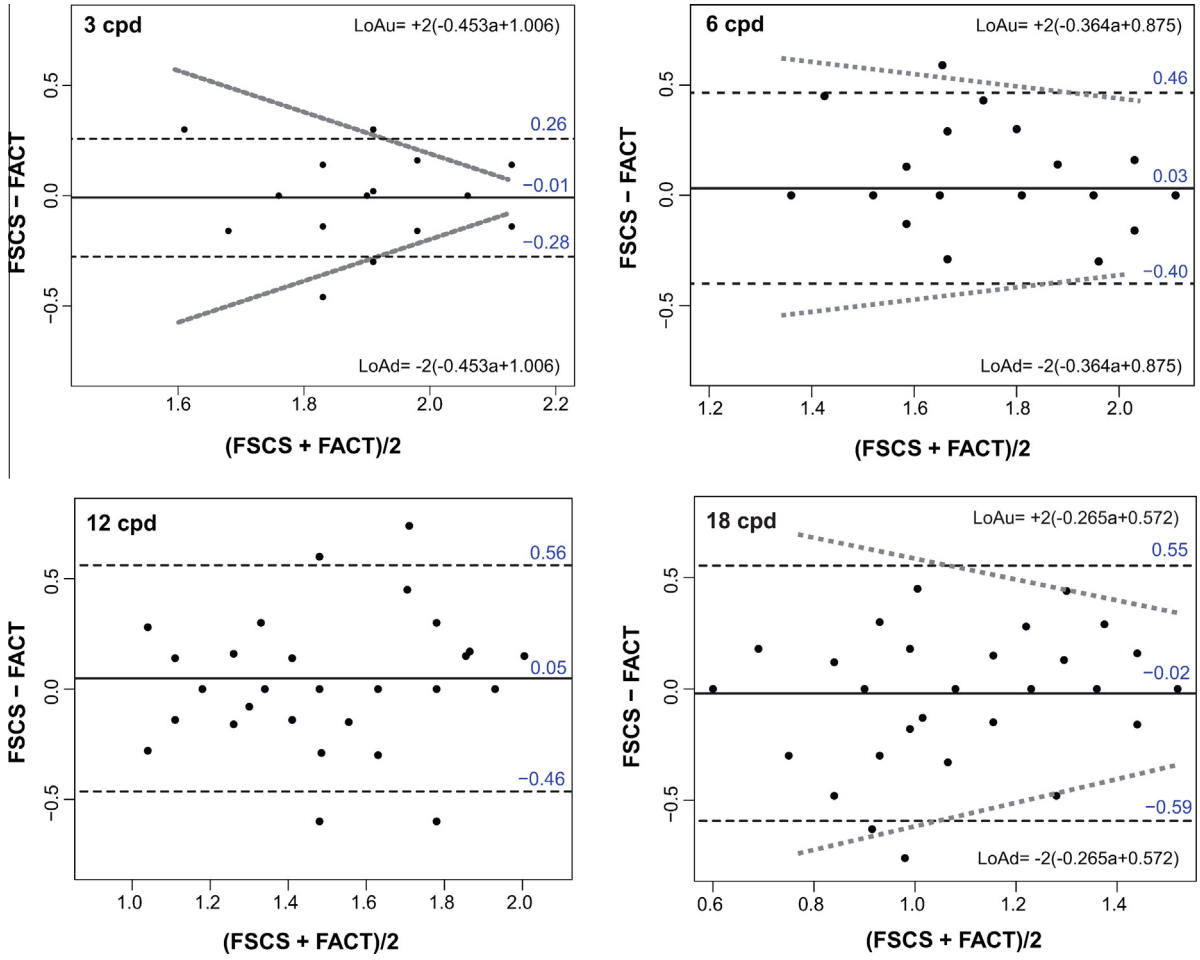

Fig. 5. Bland–Altman plots showing the mean difference against the average of FSCS and FACT. Mean differences were nearly zero for all spatial frequencies even though the limits of agreement (dashed lines) were increased with the spatial frequency and with the decrease in average of contrast sensitivity for 3, 6 and 18 cpd. The variable *a* in the LoAs equations corresponds to the contrast sensitivity average from both tests. FSCS: Fast Screening Contrast Sensitivity, FACT: Functional Acuity Contrast Test, cpd: cycles per degree.

Table 2
Mean differences and limits of agreement (FSCS-FACT) calculated by exchangeable replicates in 25 subjects who completed the tests in three different days. Coefficients of reproducibility and a non-parametric analysis of variance are also represented. FSCS: Fast Screening Contrast Sensitivity, FACT: Functional Acuity Contrast Test, MD: Mean Differences, LoAs: Limits of Agreement, cpd: cycles per degree.

	MD	LoAs	Reproducibility (*r*)		Friedman χ^2 (2, n = 25)	
			FSCS	FACT	FSCS	FACT
3 cpd	−0.01	0.30	0.31	0.19	0.92 ($p = 0.63$)	0.95 ($p = 0.62$)
6 cpd	−0.01	0.43	0.36	0.31	0.85 ($p = 0.65$)	1.40 ($p = 0.50$)
12 cpd	0	0.55	0.50	0.31	0.24 ($p = 0.89$)	1.71 ($p = 0.43$)
18 cpd	−0.03	0.56	0.53	0.42	2.47 ($p = 0.29$)	0.29 ($p = 0.88$)

Therefore, it is possible that the FSCS and FACT reliabilities also vary in subjects who present any ocular disease that affects the CSF. FSCS has several advantages in regards to the Kollbaum et al. test, including testing individual spatial frequencies; random presentation of grating orientation, to avoid the learning effect.

5. Conclusion

In this work we have presented an iPad application for screening visual performance by measuring VA and CS. We have shown that the FSVA improves the test-retest reliability compared with ETDRS. It is important to note that, even though we applied little modifications to the ATS in order to reduce time of testing (such as skipping the reinforcement phase), the reliability of the method has not been reduced. Therefore, we can conclude that the reinforcement phase in the ATS procedure might not be necessary to improve its reliability. Furthermore, we also found lower (non-statistically significant) differences between eyes with FSVA than with the EDTRS, this fact could be an advantage in screenings for amblyopia, providing a lower rate of false positive referral rates [35].

Further improvements in FSVA protocol are in progress and include the variation of letter contrast and a user calibration for its use at several test distances. In the first case this will be an interesting feature, for example, in studies of perceptual learning in amblyopia cases [37]. In the second case, the FSVA could be used, for instance, as test for the assessment of visual performance with multi-focal intraocular lenses or multi-focal contact lenses.

Regarding FSCS, further developments are directed to find the best contrast sensitivity levels for an iPad and to improve the reliability employing a best suited psychophysical method.

Finally, taking into account that each display model will need a different calibration. Future versions of the software could include several set-ups that could be selected by the user, according to the display in use.

As a final conclusion, we have demonstrated that the application we proposed is an efficient alternative in screening against more expensive large-format instruments that are difficult to transport and store, such as Optec6500. It can be very useful as a clinical tool for VA and CS screening of school-age children or older populations and it is fast, easy to perform and inexpensive. The method allows the procedure's standardization even when more than one examiner performs the test.

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