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Stereopsis assessment at multiple distances with an iPad application ☆

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ABSTRACT

We present a new application for iPad for screening stereopsis at multiple distances that allows testing up to ten levels of stereoacuity at each distance. Our approach is based on a random dot stereogram viewable with anaglyph spectacles. Sixty-five subjects with no ocular diseases, wearing their habitual correction were measured at 3 m and 0.5 m. Results were compared with a standard stereoscopic test (TNO). We found not statistically significant differences between both tests, but our method achieved higher reproducibility. Applications in visual screening programs and to design and use of 3D displays, are suggested.

1. Introduction

Visual perception of depth relies on the interpretation of different depth cues. As a consequence of the horizontal separation of the two eyes, the images of a given object in the left and right retinas are slightly different, producing the retinal binocular disparity. The ability to perceive depth through the analysis of the horizontal disparities present in the two views from the eyes is known as stereopsis. In fact, true stereoscopic 3D cannot be perceived unless both images contain different perspectives of a scene [1]. The smallest binocular disparity that can be detected is known as stereoacuity or stereothreshold. Screening of stereopsis in normal subjects could provide relevant data to be taken into account by designers of artificial 3D vision systems since the mean levels of stereopsis could be relevant to prevent undesired effects like crosstalk and visual fatigue [2–4]. Furthermore, testing stereo acuity is important in applications involving stereoscopic visualization, in particular when stereoscopy is needed to perform certain critical tasks, like surgeries or VR training. In fact, as pointed out by Gadia et al. [5], in these activities, it is often necessary an accurate assessment of stereoscopic abilities of the involved subjects. In their work, they proposed a method to assess stereo acuity and stereo blindness directly on the specific device adopted for the tasks to perform. On the other hand, the assessment of stereoacuity is of importance for ophthalmologists and optometrists, because stereo deficiencies occurs in various ocular conditions, including amblyopia ('lazy eye'), and strabismus [6–8]. In spite of these facts, in a recent review, Heron and Lages [9] found that the prevalence, as well as the degree of binocular dysfunction and stereo deficits, is relatively unknown in the general population. In some of the reviewed works, the presence or absence of stereoscopic ability was investigated; however; the individual's level of depth discrimination was not reported. Moreover, these authors pointed out that there is no agreed standard for testing stereo capabilities of the observers.

Several stereo tests, developed for clinical purposes by eye care professionals and vision researchers, are being used to screen for deficits in stereo perception, being the TNO test, the Lang I and II tests, and the Random-Dot E test the most common ones [10]. These tests use anaglyph or polarized targets and glasses to obtain several degrees of retinal disparity between the left and right eye. Two superimposed panels with random dot stimuli are presented to the observer. The ability to correctly identify a specific target is used to determine the threshold for stereopsis.

Different works compared the validity and reliability of different stereo tests and their agreement, reporting controversial conclusions [9–12]. Differences in these studies can be justified taking into account that stereoscopic visualization depends on different parameters, like the display duration of the stereoscopic views, the dimension and resolution of the stereoscopic display,

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and the distance between the display and the viewer. Most of the studies in the literature were done with stereopsis tests designed to be performed at near distances. However, in the last decade, stereo-testing at far distances has been also suggested as an important screening procedure, because it is highly sensitive to detect: small refractive errors, heterophorias, strabismus, and low visual acuities [13,14]. In spite of these facts, distance stereopsis measurements are still very uncommon, perhaps because there are few tests designed to measure distance stereopsis, being many of them also expensive and/or cumbersome.

New vision tests have been developed in recent years with the popularization of portable devices such as IPad or Android Tablets, and smartphones [15–20]. Advantages of portable computerized tests are related to their versatility and applicability in screening procedures: i.e.; remote connection, automated scoring, universal screen calibration, normal population databases, multipurpose tests, etc. Following this stimulating trend, and since the inclusion of validated stereopsis tests in this set of tablet applications is of primary importance, the main goals of this work are: to present a new iPad application for the measurement of stereopsis at multiple distances and to assess its reliability.

2. Materials and methods

2.1. Stereopsis test design

Our approach for the development of the Tablet Stereo Test (TST), is based on the Howard Dolman principle, schematized in Fig. 1. Two vertical rods are located at a given distance in front of the subject, one rod (O) is fixed, and the other one (O′), is movable back and forth along a lane. The observer task is to align the movable rod, with a string attached to it, until he or she perceives that both rods are at the same distance. The stereoacuity (γ) in radians is defined in a continuous scale from the measurement of the relative distance between the two rods along the line of sight (Δz) as:

$$\gamma = \frac{a\Delta z}{z^2}, \tag{1}$$

where z is the distance from the observer to the fixed rod (usually 3 m) and a is the interpupillary distance (see Fig. 1).

In stereograms, instead of physically arranging test targets at different distances of the observer, a pair of 2D images, each corresponding to the patient's right and left eyes field view, are presented superimposed (a stereoscopic pair) at a given fixed distance. In this way, as shown in Fig. 1, back to front position differences in three-dimensional object space (Δz) are represented as left to right (x) differences in the stereoscopic pair.

In our application, two arrays of random colored dots (one in red and the other one in cyan) are displayed simultaneously in such a way that each array should be visible with only one eye of a subject wearing anaglyph spectacles. The stimulus that creates the binocular disparity is a circle with a gap, in which the red and cyan dots are laterally displaced one respect to the other. The binocular fusion of both patterns simulates a stereoscopic object (see Fig. 2). Our choice for the colors of the stimuli, expressed in hexadecimal notation, was 0x80FF0000 for the red dots and 0x8000FFFF for the cyan dots. The spectra of the display (I-Pad retina) with these stimuli are shown in Fig. 3A and B, respectively. The spectral transmission of the corresponding filters in the anaglyph glasses are shown in Fig. 3C and D. From these figures, a certain amount of "crosstalk" between the left- and right-eye image channels could be expected. In fact, crosstalk is a primary factor affecting the image quality of stereoscopic displays [21]. From the values represented in Fig. 4E and F, the crosstalk, computed as the ratio between the "leakage" and the signal ($\times$100), in our experimental setup was 6.96% for the red channel, and 9.07% for the cyan channel. Thus, the amount of light that leaks from one stereoscopic image channel to another was very low [22].

When performing the test, the task for the observer is to identify the position of a missing section of a circle that appears at one of four possible orientations. Referring again to Fig. 1, if the displacement between the corresponding dots images at the reference (iPad) plane, is x; the stereoacuity can be expressed as $\gamma \approx x/z$ provided that $|z| \gg |\Delta z|$. Then, the stereopsis, can be computed (in radians) as:

$$\gamma \approx \frac{i}{SPDz_0}, \tag{2}$$

where SPD is the screen's pixels density, in pixels per inch (ppi), and i is the number of pixels of displacement corresponding to the observation distance z_0. In order to evaluate the same level of stereopsis at multiple distances z_j (greater than z_0), an integer multiplicative constant ($k = z_j/z_0$) must be inserted on the right member of Eq. (2). The display resolution imposes a limit on the finest value that can be measured. For the iPad *retina* this limit is 40 arcsec for $z_0 = 0.5$ m. In our application the SPD value is automatically recovered from the tablet by means of the programming code in order to avoid the need to calibrate the stimulus size. On the other hand, the size of the random dots is variable with the presentation distance in a way that each dot subtends an angle of 1.32′ at all distances which corresponds to a minimum visual acuity of 0.1 logMAR. The stereoscopic stimulus size is constant and subtends 1.88° at 3 m. For each distance of presentation, the stereoacuity scale is divided in ten discrete levels, (see the values in Table 1).

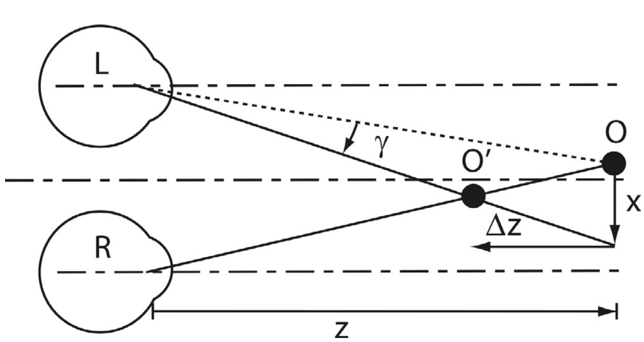

Fig. 1. Howard-Dolman scheme for computing the stereoacuity.

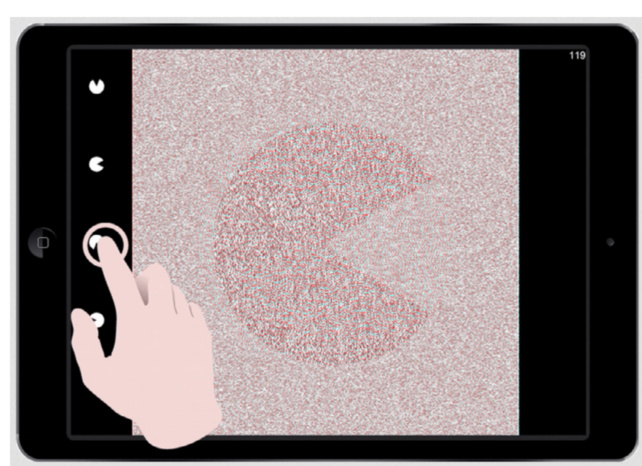

Fig. 2. TST test on iPad.

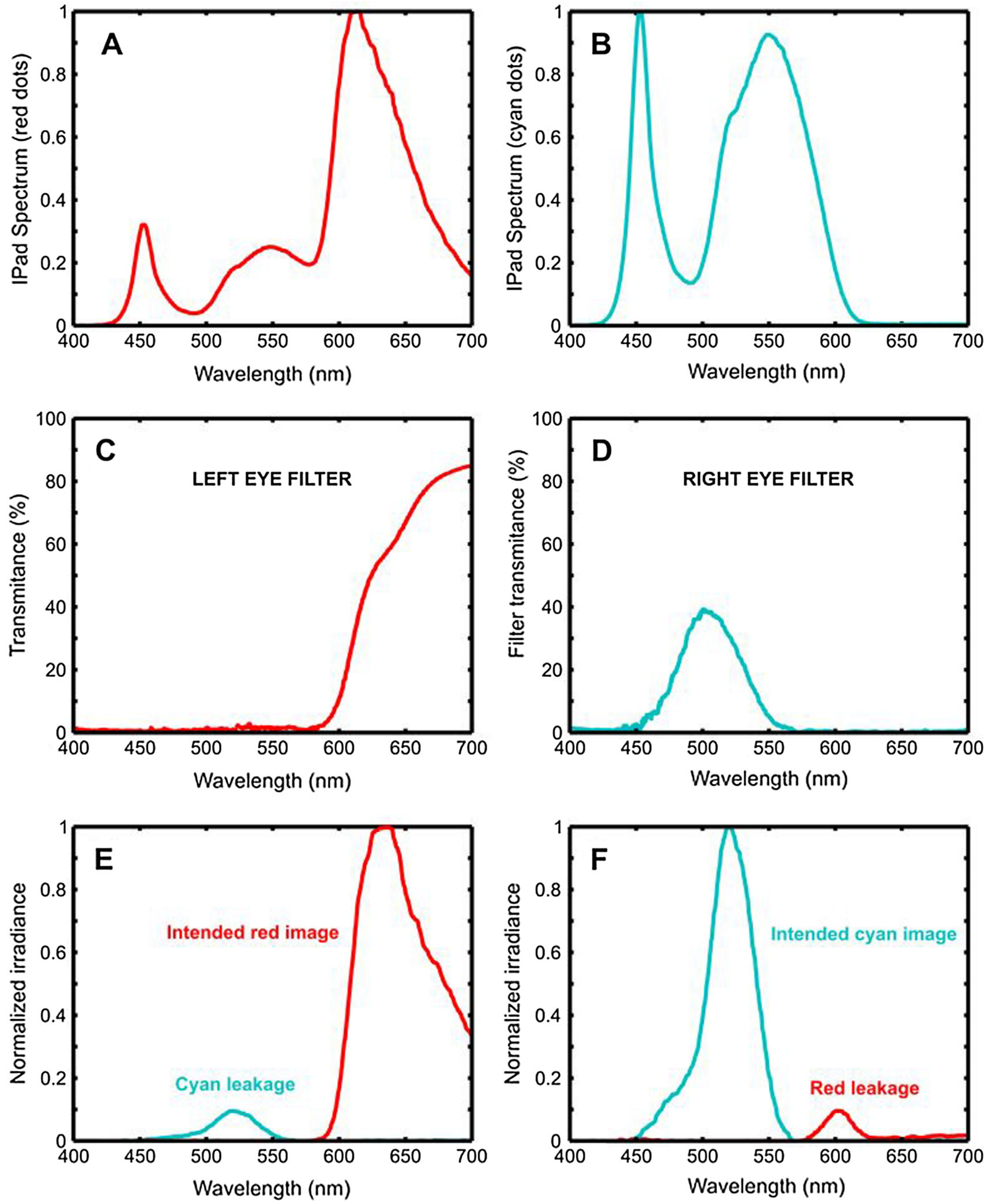

Fig. 3. Color spectrum of the IPad retina for the two channel images: (A) Red dots. (B) Cyan dots. (C) Spectral transmission of the red filter. (D) Spectral transmission of the cyan filter. (E and F) Intended irradiances and crosstalk in each channel. Measurements were performed with a compact spectrometer (CCS200/M - Thorlabs). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The TST software was developed by using pure ActionScript 3.0 programming language, and then compiled for IOS with Adobe Flash Builder (Adobe Systems, Inc.). The different threshold levels were programmed for different test distances, from 0.50 m to 3.00 m, in steps of 0.50 m. During the test, the answers of the observer were registered by the practitioner (see Fig. 2). A staircase method was also programmed in the app. In it, the level of stereopsis goes one level down with each right answer until the subject fails, then stereopsis goes one level up after the patient fails again. Stereo-threshold was recorded automatically as the last level on which subject's response is correct after the second fail.

2.2. Subjects and procedures

We have tested our method with 65 subjects (mean age: 27.7 ± 7.2 years). Participants were recruited during a vision screening at the University of Valencia. Informed consent was obtained from each subject and the research was conducted in accordance with the principles laid down in the Declaration of Helsinki. Monocular visual acuity, objective refraction and interpupillary distance, were measured before conducting the stereopsis tests with the subject wearing the habitual correction in spectacles or contact lenses. Exclusion criteria included ocular diseases, stra-

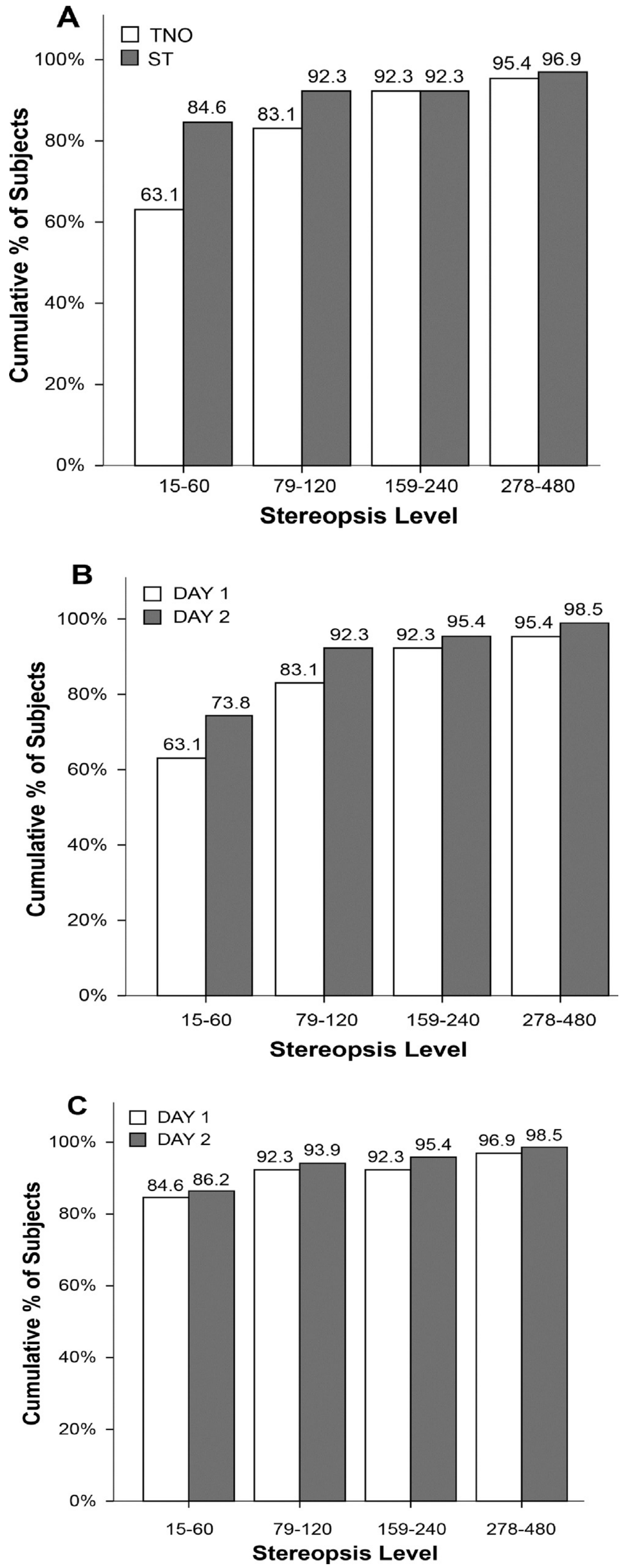

Fig. 4. Cumulative percentage of subjects who achieved a value of stereopsis in the ranges shown in Table 1. (A) comparison between TST and TNO (one day), (B) Reproducibility of TNO (two days) (C) Reproducibility of TST (two days).

bismus, monocular visual acuity less than 0.1 logMAR, difference of 0.1 logMAR between both eyes with the best correction, and a residual uncompensated refractive error, higher than ±0.50D from the objective value measured with the WAM-5500 autorefractometer (Grand Seiko Co., Ltd., Hiroshima, Japan).

The TST application was implemented on an iPad retina third generation display (2048-by-1536-pixel resolution and 264 ppi) with brightness at 100%; which corresponded to 342 cd/m^2 for white color (Spyder4Elite colorimeter). All Measurements were performed in the same room under artificial lighting conditions (a fluorescent tube bulb from ceiling lights) [23]. The horizontal illuminance at the TST presentation height: 120 cm from the floor, was 285 lux (LX1330B luxmeter). The stereoacuity was measured with TST at two different distances 3 m (far) and 0.5 m (near), taking care for avoiding any light reflection over the screen disturbing perception of the test. In each case, the stereoacuity was measured for ten different threshold levels. To validate our results near stereoscopic thresholds were also measured with a commercial TNO test using the instructions given by the provider. Since TST and TNO, both measure different discrete levels of stereoacuity, measurements were grouped in 4 sets of values (see Table 1). In order to assess the reproducibility of each test, a second set of measurements were conducted a week later on each subject.

2.3. Statistical analysis

Non-parametric statistics were used in our analysis because of the non-normal distributions of the variables. Median significant differences between intersession measurements were evaluated with the Wilcoxon Signed Rank test. The agreement and reproducibility were computed with the Cohen's k with quadratic weights. Statistical analyses were performed using the SPSS software (ver. 20; SPSS Inc., Chicago, IL, USA) and MedCalc (ver. 12.7; MedCalc Inc., Belgium). The significance was accepted at the $p < 0.05$ level.

3. Results

The comparative results for near stereopsis are shown in Fig. 4A. As can be seen, the median values of the stereopsis were slightly better for TST than for TNO even though no statistically significant differences were found in the comparison of medians between both tests ($z = -0.916$, $p = 0.36$). 84.6% of subjects achieved the finest level of 40 arcsec with the TST whereas 63.1% perceived the 60 arcsec value with TNO. From the latter group, only six subjects perceived the 30 arcsec plate and only one subject the 15 arcsec plate. The cumulated percentage of subjects who achieved the second level of stereopsis was closer for both tests, 83.1% with TNO and 92.3% with TST, and were equal at the third level (see Fig. 4A). The Cohen's k for quadratic weights resulted in substantial agreement k = 0.604. The 95% confidence interval (CI) between both instruments was [0.300, 0.908], according with Landis & Koch criteria [24]. Only one subject failed to perceive stereopsis with TST and TNO at both days whereas two subjects failed the TNO at the first day but not the TST. On the contrary, one subject failed the TST but not the TNO also at the first day.

Regarding repeatability, statistically significant differences were found for the median of both days with the TNO ($z = -3.112$; $p = 0.02$) but not with the TST ($z = -1.034$; $p = 0.301$) (see Table 2). In addition reproducibility was better with TST (k = 0.801, CI 95% [0.584, −1.000]) than with TNO (k = 0.715, CI 95% [0.520, −0.909]). This poorer reproducibility of TNO was more remarkable for the first two levels of stereopsis (see Fig. 4B and C).

At far, no significant differences in the median were found between days with TST (see Table 2); even though a poorer reproducibility than near was obtained (k = 0.502 95%CI [0.356–0.648]).

Table 1
Discrete levels of Stereoacuity with TST for far and near distances, and TNO at near. Four levels were defined (groups 1–4) to perform the *Cohen's kappa* coefficient statistic, with quadratic weights.

<table>
<tr><th colspan="3">Stereo Test</th><th colspan="2">TNO</th></tr>
<tr><th>Levels</th><th>FAR values (arcsec)</th><th>NEAR values (arcse)</th><th>NEAR Values (arcsec)</th><th>Grouped Levels</th></tr>
<tr><td>1</td><td>7</td><td>40</td><td>60, 30, 15</td><td>1</td></tr>
<tr><td>2</td><td>13</td><td>79</td><td rowspan="2">120</td><td rowspan="2">2</td></tr>
<tr><td>3</td><td>20</td><td>119</td></tr>
<tr><td>4</td><td>26</td><td>159</td><td rowspan="3">240</td><td rowspan="3">3</td></tr>
<tr><td>5</td><td>33</td><td>199</td></tr>
<tr><td>6</td><td>40</td><td>238</td></tr>
<tr><td>7</td><td>46</td><td>278</td><td rowspan="4">480</td><td rowspan="4">4</td></tr>
<tr><td>8</td><td>53</td><td>318</td></tr>
<tr><td>9</td><td>60</td><td>357</td></tr>
<tr><td>10</td><td>66</td><td>397</td></tr>
</table>

Alternate white and grey rows, correspond to different grouped levels (1-4).

Table 2
Reproducibility analysis between days with TST and TNO. Wilcoxon and Cohen's K were computed in order to assess the difference in medians and the concordance, respectively.

		Median (arcsec) [interquartile range]	Wilcoxon	Cohen's k [95% CI]
ST Far	Day 1	26 [20–46]	z = −0.992, p = 0.321	0.502 [0.356–0.648]
	Day 2	26 [13–53]		
TNO	Day 1	60 [60–120]	z = −3.112, p = 0.020	0.715 [0.520–0.909]
	Day 2	60 [60–90]		
ST Near	Day 1	40 [40–40]	z = −1.034 p = 0.301	0.801 [0.584–1.000]
	Day 2	40 [40–40]		

4. Discussion and conclusions

In this paper, we have presented a new stereoacuity test (called TST). Our method, which is an app to be performed on an iPad, is to the best of our knowledge the first test that can be used for screening stereopsis at multiple distances with a portable device. To validate our proposal, we have compared our results with those obtained with a standard card-based stereoacuity test (TNO Test) on 65 subjects. From the analysis of the results, the TST achieved more reproducible results, but no statistically significant differences were found.

The TST could be useful in the design 3D displays to study the tolerance range of binocular disparity in order to prevent visual discomfort [2–4]. Moreover, our proposal is of value for eye care professionals to monitor binocularity, for instance: in vision therapy, or after cataract surgery [25,26]. On the other hand, distance stereopsis measurement has been suggested to be more effective than near stereopsis testing, in screening for binocular vision disorders, reduced visual acuity, and uncorrected refractive error [14,27–29]. In spite of its usefulness there are not many commercial tests to measure distance stereopsis. Therefore, to have a single and non-expensive test for measuring stereopsis at multiple distances could be of major benefict.

The main limitation of our method is that the minimum measurable levels of stereoacuity depend on pixel size; [30] therefore, the limit for the iPad Retina (264 ppi) at 0.5 m is 40 arcsec. However, finer values of stereopsis at near could be evaluated with tablets or phones with highest SPD (i.e., with iPhone 6 or iPad mini which have 326 ppi. Additionally, we found a small amount of "crosstalk effect" between the red and cyan channels, due to the combination of the spectral performance of the filters and the IPad spectral emission. Further studies are required to determine the impact of the crosstalk effect with different anaglyph glasses in the performance of the TST. A calibration procedure could be included in the app in order to select the colors that best fit a given anaglyph glasses.

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