MSc in Photonics

PHOTONICS**BCN**

Universitat Politècnica de Catalunya (UPC)
Universitat Autònoma de Barcelona (UAB)
Universitat de Barcelona (UB)
Institut de Ciències Fotòniques (ICFO)

http://www.photonicsbcn.eu

Master in Photonics

MASTER THESIS WORK

Clinical validation of a fast binocular subjective refraction algorithm

Rocío García García

Supervised by Dr. Jaume Pujol Ramo and Mr. Carles Otero Molins (Davalor Research Center-Universitat Politècnica de Catalunya)

Presented on date 8th of September 2017

Registered at

Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona

Clinical validation of a fast binocular subjective refraction algorithm

Rocío García García
Davalor Research Centre (Gaia Building), Universitat Politècnica de Catalunya (UPC), Rambla Sant Nebridi 22 - 08222 Terrassa (Barcelona, Spain)

E-mail: rocio21garcia@gmail.com

Abstract. The purpose of this study is to investigate a new algorithm to perform an automated non-cycloplegic refraction in adults. In order to carry on the study fifty healthy subjects were measured twice (test-retest) with the new automated subjective refraction (ASR) method and with the conventional clinician subjective refraction (CSR) procedure. Objective refraction (OR) is also measured with the autorefractor Grand Seiko WAM-5500. The new subjective refraction procedure is mainly based on the root finding bisection algorithm and on the Euclidean distances among power vectors. The algorithm is implemented on a computer that is synchronized with a custom-made motorized phoropter. Main outcome measures: spherical equivalent (M) and Jackson cross-cylinder (J0 and J45). Repeatability is assessed with the within-subject standard deviation (Sw) and agreement is assessed with the limits of agreement. The results showed that the first implementation of the algorithm is a potential novel method of performing non-cycloplegic subjective refraction in adults without clinician support. Although it presents some limitations that warrant further research and it still should be tested in a wider population in terms of age, refraction and different ocular conditions, this method can contribute to improve the access to primary eye care services in developing countries.

Keywords: refraction, automated, phoropter, subjective.

1. Introduction:

According to the most recent estimates from the World Health Organization (WHO), the uncorrected refractive error is the main cause of visual impairment, affecting 43% of the global population.[1]The largest prevalence of visual impairment is found in developing countries, for which there is evidence that one of the leading causes for uncorrected refractive error is the insufficient eye care personnel and massive imbalance in the distribution of eye care services in these countries.[2] Automated and portable technology capable of performing accurate non-cycloplegic refractions could help to reduce this problem.

Eye's refraction can be obtained both objectively and subjectively. Objective refraction measurements can be currently determined fast and easily with autorefractors and wavefront aberrometers and they are often used as a starting point for conventional subjective refraction.[3] However, prescribing from objective findings alone achieves limited patient satisfaction and visual acuity does not improve sufficiently.[4]

Subjective refraction is based on comparing different dioptric lenses (i.e., spherical and cylindrical lenses) and measuring changes in visual acuity to arrive at the dioptric lens combination that maximizes it.[5] In contrast to objective refraction, subjective refraction relies on the response of the patient and on the examiner's skills. These two factors may be the reason why some authors found more variability in subjective refraction than in objective refraction outcomes.[6] However, Rosenfield and Chiu[7] found no differences in variability, they obtained mean standard deviations for the subjective and objective techniques of ± 0.15 D and ± 0.14 D, respectively.

Subjective refraction is a challenging procedure especially when not using cycloplegia to minimize accommodation artefacts in non-presbyopes. This is the case of pseudomyopes[8] or latent hyperopes,[9] in both situations a cycloplegic refraction to obtain the full refractive error is recommended and spectacle prescription should be based on careful consideration of the patient's individual visual needs.[4-10] It is likely that an automated non-cycloplegic refraction algorithm will not substitute cycloplegic refractions under these circumstances but it can be useful as a screening automated method if embedded in a cost-efficient device. Recently, new technologies have appeared with the aim of approaching eye's refraction to general population in a more affordable way, [11] although none of them include the patient's psychophysical response, which limit their applicability for screening purposes or spectacles prescription. Having all this in mind, the purpose of this study is to propose an algorithm to perform an automated non-cycloplegic refraction in adults.

2. Methods:

2.1. Instrument:

For a 'proof-of-concept' of the algorithm we converted a manual phoropter into a motorized system. We partially disassembled a commercial manual phoropter (VT-10, Topcon Co. Ltd., Japan) and introduced 8 motors (4 for each eye) that allowed to control the sphere power, cylinder power, cylinder orientation and the occluder of each eye independently. All motors were connected to the drivers which in turn were connected to a computer with a USB wire and controlled via Matlab R2015b. A display connected to the computer was placed at 6 meter distance from the observer and was used as the stimulus display (monitor Philips 246V with 24 inches and 1920x1080 pixel resolution). A wireless keyboard was used by the observers to provide feedback to the algorithm. A picture of the setup is shown in figure 1.

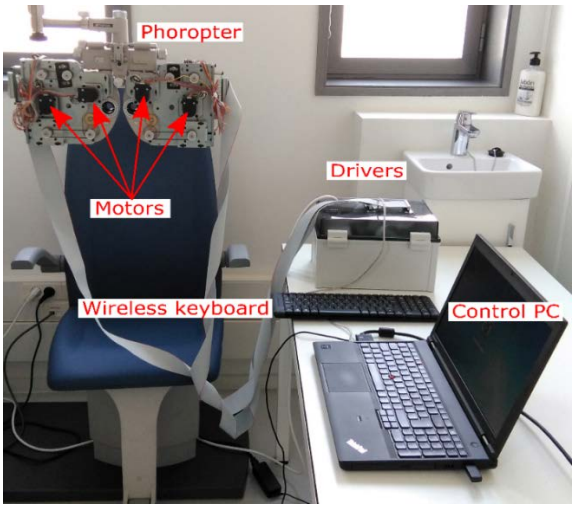

Figure 1. Picture of the clinical setting with the custom-made motorized phoropter. Four motors are attached in the anterior surface and 4 motors are attached in the posterior surface of the phoropter. Motors are connected to the drivers and a USB wire connects the drivers to the control PC. The wireless keyboard is used by the observer to respond (e.g., to respond to stimulus orientation: up, down, left or right).

2.2. New method algorithm:

The automated subjective refraction algorithm receives two inputs:1) the current objective refraction (obtained with an autorefractometer or wavefront sensor); 2) the previous spectacle prescription (obtained either with the last prescription record or measuring the sphero-cylindrical power with a fronto-focimeter of the current spectacles worn by the observer). If the observer has never been prescribed any corrective glasses, we considered a 0 value for the sphere, cylinder and axis in both eyes. If the observer does not wear the spectacles at the time of the examination and the last prescription record is not available we considered a NULL value for sphere, cylinder and axis in both eyes.

Once the two inputs are obtained, the algorithm goes through a sequence of 6 functions (figure 2) detailed in order as follows:

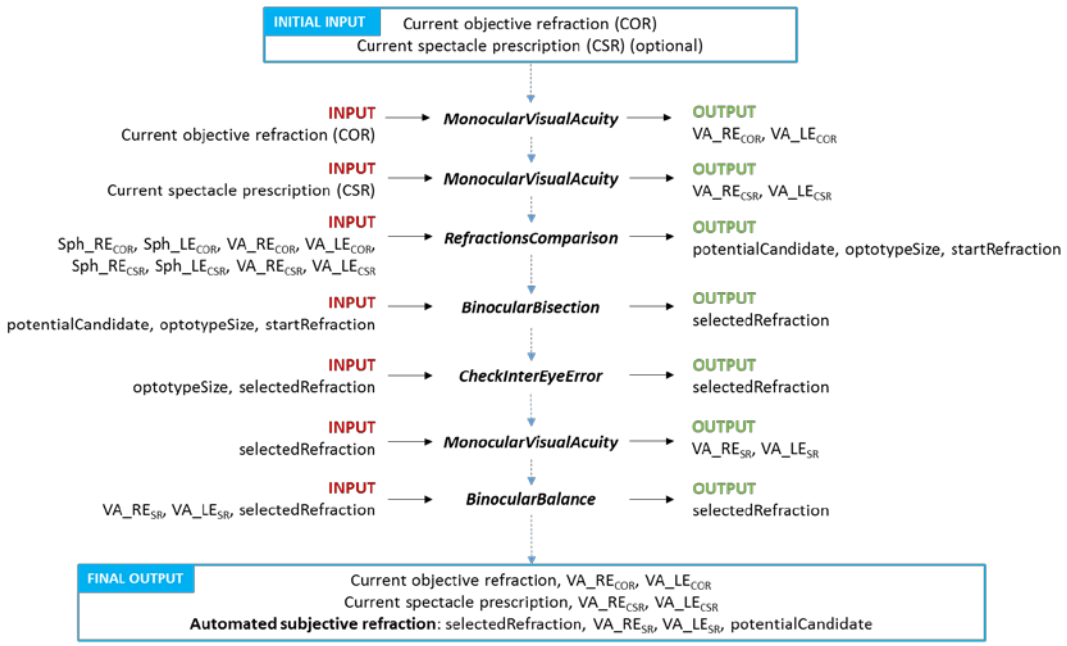

Figure 2. Flux of the automated subjective algorithm with all input and output variables for each function. VA: Visual Acuity. RE: Right Eye. LE: Left Eye.

1. *Monocular Visual Acuity function:*

This function receives as an input 6 values: the sphere, cylinder and axis values of each eye. This function tests the observers' monocular visual acuity in a four-alternative force-choice task (4AFC). A black Snellen optotype (figure 3) is displayed at a visual acuity of 0.1 logMAR and the observer is required to select the correct orientation of the letter by pressing the arrows of a computer keyboard (i.e., up, down, left, right). This process is repeated 3 times to reduce the guess rate while the orientation of the Snellen 'E' randomly changes each time. If the observer selects 2 out of the 3 times correctly, the optotype size is decreased in steps of 0.1 logMAR, otherwise the optotype size is increased in steps of 0.1 logMAR until the observer reports 2 out of the 3 orientations correctly.

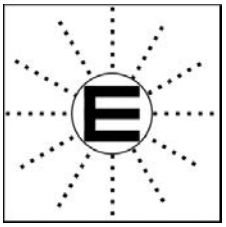

Figure 3. The stimulus used during the automated subjective refraction.

2. *Refractions Comparison function:*

This function receives as an input 8 values: the sphere of each eye from both the current objective refraction and current spectacle prescription as well as the corresponding visual acuities measured at the beginning of the method (figure 2). The aim of this function is: 1) to detect potential pseudomyopes or latent hyperopes; 2) to determine the starting point of refraction and the optotype size used in the next functions.

If the sphere of the current objective refraction minus the sphere of the current spectacle prescription is equal or more than 0.75D the observer is considered a potential pseudomyope or latent hyperope. Notice that it is a signed difference, only when the observer's current spectacle

refraction is more negative than the objective refraction the observer can be considered a potential pseudomyope or latent hyperope. Pseudomyopes is the term used for negative subjective spherical refractions whereas latent hyperopes is the term for positive subjective refractions in the presence of excessive accommodation.[10] The cut-off value of 0.75D is based on the precision of subjective refraction, as suggested by Rosenfield and Chiu.[7] It is also important to remark that this way of detecting pseudomyopes or latent hyperopes assumes that the non-cycloplegic autorefraction will be as accurate as measured in a cyclopleged eye, which is true for young adults of approximately 20 years of age.[12] This is the main reason why we will not consider subjects younger than 20 years of age in this study.

The starting point of refraction to be used in the next function is determined as the refraction (either the current objective refraction or current spectacle prescription) with the best visual acuity, which is computed as the average between the right and left eye's visual acuity. Notice that if both averages are equal, current spectacle prescription input is NULL, or a potential pseudomyope (or latent hyperope) is detected the current objective refraction is chosen as starting point of refraction. The optotype size for the next functions is computed as the maximum visual acuity between the right and left eye's starting point of refraction.

The output of this function is a variable named *potential Candidate* that can only have three values: *true*, *false* or NULL. *True* is for potential pseudomyopes or latent hyperopes, *false* for observers that are not, and NULL is the output in the case the values from current spectacle refraction are NULL. Other outputs of this function are the optotype size (in logMAR units) and the starting point of refraction.

3. Binocular Bisection function:

This function receives as input the output of the previous function *Refractions Comparison*. *Binocular Bisection* starts setting a range of refractions which assumedly comprise the final subjective refraction and over which the algorithm will test the subject's blur perception. This range is calculated according to the input refraction and the *potential Candidate* variable (an estimation of a potential pseudomyope or latent hyperope).

On the one hand, when *potential Candidate* equals to *false* the algorithm considers a range for the sphere (R_S) that goes from -0.50 to +1.50 D with respect the input sphere (R_S=2.00D). If the input sphere comes from the current objective refraction, since autorefraction and wavefront sensors tend to result in more minus correction than the subjective refraction,[13] a longer positive range than a negative one increases the odds to find the optimum subjective refraction.

On the other hand, when *potential Candidate* equals to *true*, the starting point of refraction comes from autorefraction or wavefront sensing by default. In this specific situation the algorithm flips the spherical range, i.e., it considers a range that goes from -1.50 to +0.50 D. As expected for a pseudomyope or latent hyperope, observers will likely choose more myopic refractions to achieve the best visual acuity. And finally, if *potential Candidate* equals to NULL, the spherical range goes from -0.50 to +1.50 D with respect the input sphere.

Regarding the cylinder power, the algorithm considers a range that goes from the input cylinder to +1.00D with respect the input cylinder power (R_C=1.00D). For axis orientation, the algorithm does not consider any set of different possible axis orientations (R_A=0 º). It is important to take into account that R_C and R_A are theoretically bounded quantities, i.e., the axis range is limited to 179º and the cylinder can range from any negative value up to 0D (considering that all input refractions are in negative cylinder notation). The arbitrary decisions of these ranges can limit the accuracy of the algorithm significantly (specially the fact of not considering any change in axis orientation). But, this new methodology can easily include a set of different axis orientations or include larger spherical and cylindrical ranges at the cost of efficiency.

Next, the step size (i.e., precision) for each variable must be established. The algorithm considered a step size of 0.25 D for both sphere (SS_S) and cylinder (SS_C). For axis orientation, a step size (SS_A) of 1º could have been considered. Once the six free parameters have been determined (R_S, R_C, R_A, SS_S, SS_C and SS_A), all possible combinations of refractions comprised within the ranges and with the specified step sizes are computed. At this point, all the generated sphero-cylindrical refractions for each eye are transformed into power vector notation (M, J_0 and J_{45}) using equations 1, 2 and 3. This transformation allows algebraic operations on the eye's

refraction in an orthogonal 3-D base (M, J_0 and J_{45}). Consequently, even if the three variables sphere, cylinder and axis are not independent from one another, they become theoretically independent when transformed into M, J_0 and J_{45}.

$$M = S + \frac{C}{2} \tag{1}$$

$$J_0 = -\frac{C}{2} cos2\alpha \tag{2}$$

$$J_{45} = -\frac{C}{2} sin2\alpha \tag{3}$$

The next step is to compute for each eye all the Euclidean distances (ED) between all the generated refractions (M_i, $J0_i$, $J45_i$, for i=1...N_{ref}) and the most negative refraction (M_1, $J0_1$, $J45_1$) as follows

$$ED = \sqrt{(M_i - M_1)^2 + (J_{0_i} - J_{0_1})^2 + (J_{45_i} - J_{45_1})^2}\,. \tag{4}$$

Notice that the most negative refraction is that with the smallest spherical equivalent (M).
Next, all the generated refractions are sorted in ascending order of Euclidean distances (figure 4). The maximum number of possible refractions follows equation 5

$$N_{ref} = round\left(\frac{R_S}{SS_S} + 1\right) \cdot round\left(\frac{R_C}{SS_C} + 1\right) \cdot round\left(\frac{R_A}{SS_A} + 1\right) \tag{5}$$

where round () is a function that rounds to the nearest integer. Note that when the 6 free parameters are provided, the number of possible refractions (N_{ref}) depends on the most negative cylinder value since it is an inferior bounded quantity (Figure 4A). Once this computation is completed, a two-interval force-choice task (2IFC) is performed inspired on the mathematical root finding bisection algorithm. A black Snellen optotype (figure 3) is shown during 4 seconds with a refraction given by one end of the sequence of refractions previously computed for each eye (e.g., M_1, $J0_1$, $J45_1$), and then the same optotype is again shown during 4 seconds with the opposite extreme refraction (e.g., M_{Nref}, J_{0Nref}, J_{45Nref}). The decision to present a certain refraction firstly or secondly is randomized.

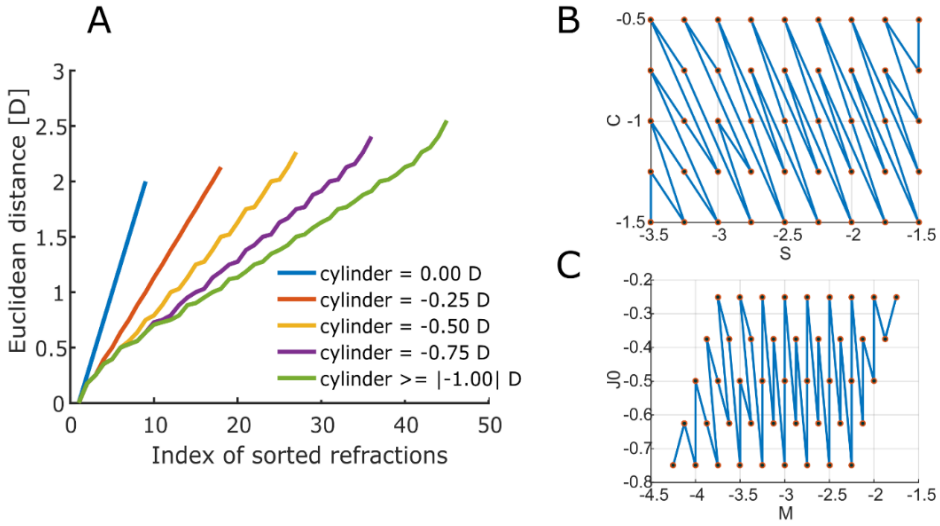

Figure 4. A: Dependence of the Euclidean distances and number of possible refractions according to the amount of cylinder of the most negative refraction (M_1, J_{01}, J_{451}). The specific case of R_S=2.00 D, R_A=0º and SS_S=SS_C=0.25 D is shown. The number of possible refractions (N_{ref}) are (in ascending order): 9, 18, 27, 36 and 45. B, C: 2-Dimensional representation of all possible sphero-cylindrical and power vector refractions (panel B and C respectively) considering the specific case of R_S=2.00 D, R_C=1.00 D, R_A=0º, SS_S=SS_C=0.25 D and a starting point of refraction of -3.00-1.50x90º. Each dot represents one refraction. The blue line connects each refraction in ascending order of Euclidean distances from the most negative refraction.

At this point the observer is required to choose which image (i.e., refraction) was the clearest by pressing either the right or left button of the keyboard. Once the observer has selected one image, in the next test the unselected refraction is changed by the refraction corresponding to the mean index refraction rounded to the nearest integer. That is, in the first pair selection, refractions correspond always to indices $i_{min}=1$ and $i_{max}=N_{ref}$ respectively, whereas in the second selection i_{min} or i_{max} correspond to round($(N_{ref}+1)/2$), depending on whether the patient selected the refraction with index $i_{max}=N_{ref}$ or $i_{min}=1$. This procedure is repeated until $i_{min}=i_{max}$ and it is performed under binocular conditions. In order to decrease the guess rate, each 2IFC trial is repeated 3 times and the selected refraction is the one chosen at least 2 times out of the 3 repetitions.

4. *Check Inter Eye Error function:*

This function receives as input the output of the *Binocular Bisection* function. This function aims to reduce the inter-eye measurement error that may come from the starting point of refraction when there is a difference in refraction (either in cylinder or sphere) of 0.75 D or more between the right and left eye's refraction. If differences between right and left eye's sphere or cylinder are less than 0.75 D the algorithm jumps directly to the next function without doing any change.

The procedure is conducted similarly to *Binocular Bisection*, where each 2IFC task compares (binocularly) the refraction obtained with *Binocular Bisection* with a refraction that reduces the inter-eye difference in at least one Euclidean distance. In the first three comparisons, the left refraction is changed one Euclidean distance closer to the right refraction, which remains completely unmodified. In the following three comparisons, the right refraction is changed while the left remains unmodified. Finally, in the last three comparisons both the left and right eye refractions are changed one Euclidean distance from each other so the distance between refractions is reduced two steps. After all these trials, the refractions of both eyes are changed according to the observer's response. Notice that when contradictory answers from the observer occur no change is produced.

5. *Binocular Balance function:*

This function receives as input the values of sphere, cylinder and axis of both eyes obtained in *Check Inter Eye Error* function and the values of monocular visual acuity obtained in the previous function. The aim of this function is to look for the maximum plus power with the same visual acuity obtained in the previous function. It is added an arbitrary value based on previous pilot studies of +0.50 D to the sphere of each eye. Then, the Snellen 'E' optotype (figure 3) is presented, binocularly, with a size corresponding to the best monocular visual acuity obtained in the previous step. The observer is required to answer the orientation of the letter in the same way it is done in the *Monocular Visual Acuity* function. If the observer answers incorrectly in 2 out of the 3 times, the miopization is decreased 0.25 D, otherwise the algorithm is finished and the final subjective refraction is the last refraction tested.

The final output of the algorithm comprises the sphere, cylinder and axis of both eyes and the monocular visual acuities of the automated subjective procedure, the current objective refraction and (when available) the current spectacle prescription. In addition, the outcome of the algorithm also includes the variable *potential Candidate* which may advice the patient to look for a cycloplegic refraction with a professional in case it is *true* or NULL.

2.3. Examination protocol:

Non-cycloplegic binocular subjective refraction was obtained twice in 50 healthy adults with the new automated method and with the conventional clinician subjective refraction procedure performed in a manual phoropter. The objective refraction was obtained with the WAM-5500 and was used as starting point of refraction for both the automated and the clinician subjective refractions. One clinician performed all subjective refractions and was blinded to the refraction results obtained with the automated method. The clinician and was specifically told to follow a refraction protocol of maximum plus power for best visual acuity. All clinical subjective refractions followed a monocular refraction plus biocular and binocular balance. Cylinder and axis orientation were refined with Jackson cross-cylinders. And the light conditions were the same for all the measurements.

2.4. Data analysis:

Statistical significance was set at 0.05 and the statistical analysis was performed using MATLAB R2015b (MathWorks, Inc., USA). Normality of each variable was verified with the Shapiro-Wilk test. Repeatability of the new method and repeatability of the clinician were analysed by means of the within-subject standard deviation (Sw). The repeatability of the autorefraction has been evaluated before, the interested reader is referred to previous published articles about it.[11,14] Agreement between the automated and the clinician subjective refraction was assessed with Bland and Altman plots for each eye and parameter, as well as the agreement between autorefraction and the clinician subjective refraction. Additionally, paired t-tests are applied for repeatability analysis and repeated measures ANOVA are applied for the agreement analysis among the three methods. Statistical power was assessed with the free open-source G*Power 3.0.10. A pilot study with 25 subjects was conducted to calculate the sample size needed for a statistical power of 0.95 and it resulted in 40 subjects.

3. Results:

The mean age ± standard deviation of the 50 observers were 30±8 years (20 to 57 years) with a mean spherical equivalent refractive error of -1.74±2.28 (-7.25 to 2.13) D and with mean corrected logMAR visual acuity of -0.06±0.07 (-0.1 to 0.2). There were 76% myopes, 20% hyperopes and 4% emmetropes. The starting point of refraction for the automated method was the current spectacle prescription 36% of the times and 0% of the subjects were considered potential candidates for pseudomyopia or latent hyperopia. On average, the new proposed method took 4 minutes and 16 seconds (±44 seconds) and the conventional standard procedure took 4 minutes and 37 seconds (±50 seconds). The time difference was statistically significant (paired sample t-test, p=0.02).

3.1. Repeatability analysis:

The mean difference ± standard deviation (SD) between both sessions (test-retest), the within-subject standard deviation (S_W) and the p-values obtained with the paired sample t-test are shown in table 1 for each eye, parameter and method.

Table 1. Repeatability (test-retest) for each eye, parameter and method. CSR: Clinician Subjective Refraction. ASR: Automated Subjective Refraction. Diff.: difference. SD: standard deviation. S_W: within-subject standard deviation.

	Repeatability CSR method			**Repeatability ASR method**		
	Mean Diff. ± SD [D]	SW [D]	p-value	Mean Diff. ± SD [D]	SW [D]	p-value
$\mathbf{M_{RE}}$	0.02±0.19	0.13	0.48	-0.07±0.23	0.17	0.04
$\mathbf{J0_{RE}}$	0.01±0.05	0.04	0.24	<0.01±0.05	0.03	0.88
$\mathbf{J45_{RE}}$	-0.02±0.07	0.05	0.01	<0.01±0.10	0.07	0.81
$\mathbf{M_{LE}}$	0.03±0.18	0.12	0.21	-0.06±0.28	0.20	0.13
$\mathbf{J0_{LE}}$	<0.01±0.06	0.05	0.98	<0.01±0.06	0.04	0.83
$\mathbf{J45_{LE}}$	<0.01±0.08	0.05	0.86	<0.01±0.11	0.08	0.61

3.2. Agreement analysis:

The Bland and Altman plots comparing the automated subjective refraction with the clinician subjective refraction are shown in figure 5. And, the Bland and Altman plots comparing between autorefraction and the clinician subjective refraction is shown in figure 6. The results of the repeated measures ANOVA considering the three methods and applied to the right eye parameters are: F=26.46, p<0.01 for M; F=2.67, p=0.07 for J_0; and F=1.37, p=0.26 for J_{45}. Analogously, the results for the left eye are: F=1.74, p<0.01 for M; F=0.14, p=0.87 for J_0; and F=2.05, p=0.14 for J_{45}.

Only the repeated measures ANOVA applied to the spherical equivalent of both eyes results in statistically significant differences among methods. The Bonferroni post-hoc test for the right and left eye shows that differences between autorefraction and clinician subjective refraction are statistically significant ($p<0.01$) as well as the differences between autorefraction and automated subjective refraction ($p<0.01$).

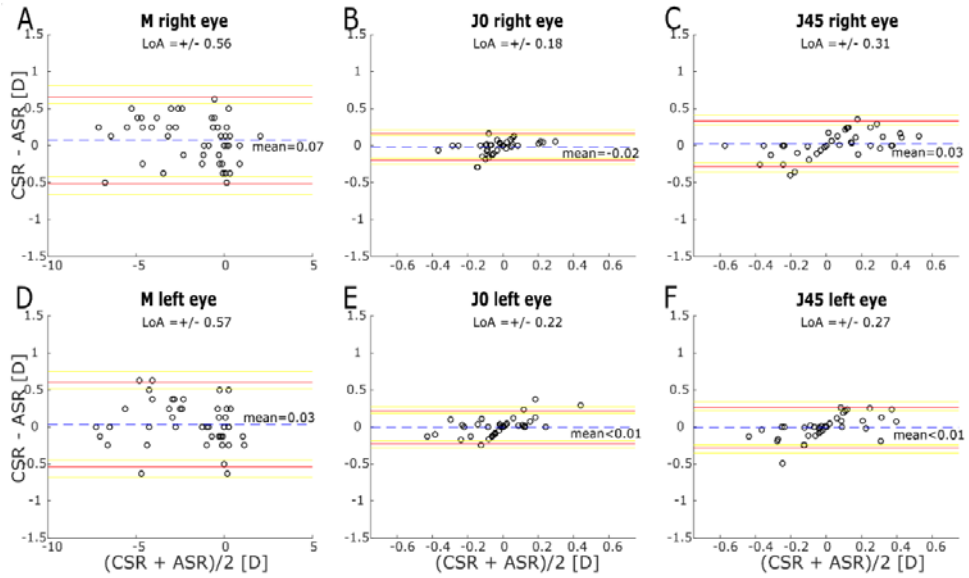

Figure 5. Bland and Altman plots. A, B, C: right eye data. D, E, F: left eye data. The top and bottom red lines indicate the superior and inferior 95% limits of agreement (LoA), respectively. The yellow lines indicate the superior and inferior 95% confidence interval for each limit of agreement. The dashed, blue lines indicate the mean difference. CSR: Clinician Subjective Refraction. ASR: Automated Subjective Refraction.

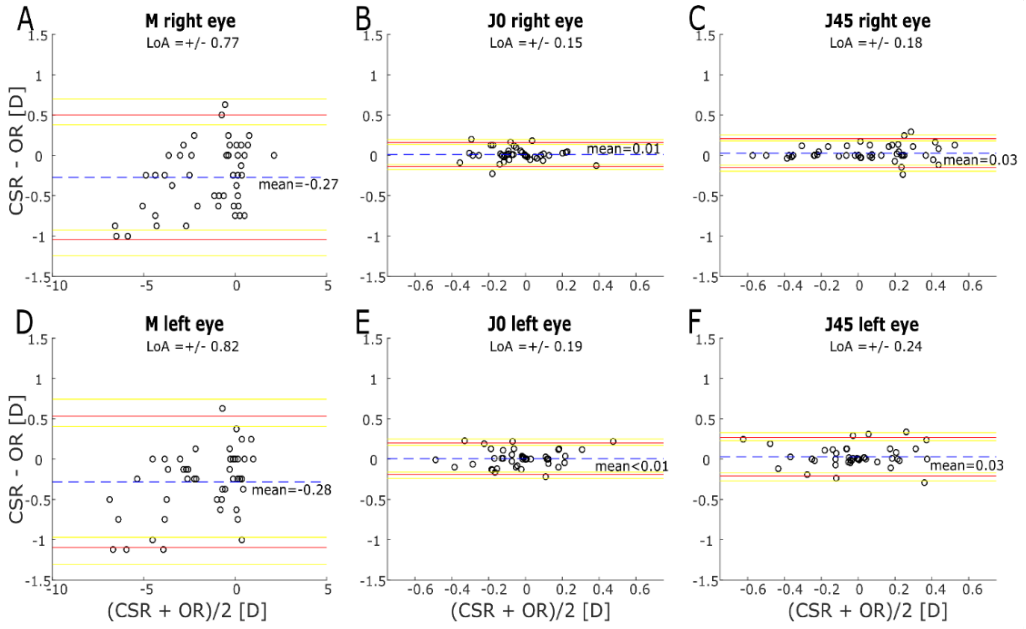

Figure 6. Bland and Altman plots. A, B, C: right eye data. D, E, F: left eye data. The top and bottom red lines indicate the superior and inferior 95% limits of agreement, respectively. The yellow lines indicate the superior and inferior 95% confidence interval for each limit of agreement. The dashed, blue lines indicate the mean difference. CSR: Clinician Subjective Refraction. OR: Objective Refraction (Grand Seiko WAM-5500).

4. Discussion:

A new method to perform non-cycloplegic binocular subjective refraction without the support of a clinician was investigated. Repeatability (test-retest) and agreement of this new method in relation to the conventional clinical procedure was assessed in 50 subjects. A total of 6 variables were analysed: the power vectors components (M, J_0 and J_{45}) of both eyes.

Our results showed that the automated subjective refraction method is not as fast as autorefractors or wavefront sensors but is slightly faster than the clinician subjective refraction. Hence, the time duration of the method does not impose a practical limitation. With respect the repeatability analysis, the within-subject standard deviations found for the automated method are comparable to those found for the clinician subjective refraction for all three components (M, J_0 and J_{45}). In all cases we obtained within-subject standard deviations below 0.25 D, which is the limit of clinical significance. Autorefractors and wavefront sensors are, in general, more repeatable since they do not depend on the patient's response or the clinician's skills. Otero *et al*.[15] analysed the repeatability (averaging 3 measurements) of a wavefront sensor (AOVA, Voptica S.L., Spain) and obtained within-subject standard deviations for the sphere of ±0.17 D. We found only three studies comparing the agreement of an automated subjective refraction method with the conventional clinical subjective refraction. Two of them used the same device (Topcon BV-1000, no longer commercially available) and they reported limits of agreement for the spherical equivalent of ±0.69 D and ±0.82 D.[16,17] The third study was performed in our lab, the automated method was implemented on a stereoscopic virtual reality system and limits of agreement of ±0.88 D were obtained for the spherical equivalent.[14] In this study, a value of ±0.59 D was obtained for the same variable. Sheppard *et al*.[3] compared autorefractor readings of the WAM-5500 with the subjective refraction and found limits of agreement for the spherical equivalent of ±0.75

Although it is accepted that objective refractions are much more precise than subjective refractions (whether or not automated), these comparisons show that the new proposed method is reasonably equivalent to the conventional clinical subjective refraction in time duration, accuracy and precision. Moreover, it incorporates two important novel factors: it does not require clinician support and it has better agreement than most objective refractometers. However, this new method still requires some improvements before it can be widely used. In terms of the astigmatic determination, the within-subject standard deviation and the limits of agreement found for the variables J_0, and J_{45} are also comparable to the previous cited studies, but an unexpected systematic linear error in the Bland and Altman plots for the J_0 and J_{45} in both eyes was observed (Figure 3B, 3C, 3E and 3F). We cannot entirely explain the source of these errors and interestingly, other studies that compared a handheld wavefront sensor to subjective refraction obtained as well these systematic errors.[11] None of these previous studies provided a clear explanation for these findings. Previous studies showed that cylinder errors of 0.5 D or less do not significantly degrade visual acuity;[18] the precision of cylinder axes determined subjectively is around ±10º;[7] and between 80% and 95% of the cylinder axes determined with an autorefractor are within 20º (or less) of those found subjectively.[4,13] Anyhow, the limits of agreement obtained for both eyes and astigmatic components are small (they are on average 0.25 D), which means that the impact of the systematic errors is on average insignificant.

Finally, our results also suggest that the automated method does not introduce significant accommodation artefacts in healthy adults in the sense that observers did not tend to significantly over-minus themselves. Although it should be remarked that only healthy adults were tested and none had any accommodative dysfunction such as pseudomyopia or latent hyperopia. Thus, from our results we cannot conclude anything about the performance of the algorithm in children or people with ocular pathologies or accommodative anomalies. Despite these limitations, overall it has been shown that the automated method is precise enough and more accurate than autorefraction and wavefront sensing in healthy adults, which makes it valuable as a preliminary step in subjective refraction and it might be especially useful where refraction take place outside a clinical setting or where clinicians cannot be present (of course, the method requires a starting point of refraction and an electro-optical system capable of changing the sphero-cylindrical refraction with the observer's feedback).

Conclusions

The first implementation of the algorithm has shown a potential novel method of performing non-cycloplegic subjective refraction in adults without clinician support. Although it presents some limitations that warrant further research and it still should be tested in a wider population in terms of age, refraction and different ocular conditions, this method can contribute to improve the access to primary eye care services in developing countries.

Acknowledgments. I would like to thank to all the patients who altruistically participated in this study.

References

1. Pascolini D, Mariotti SP. Global estimates of visual impairment: 2010. *Br. J. Ophthalmol.* 2012;96(5):614-618.
2. Ilechie AA, Otchere H, Darko-Takyi C, Halladay AC. Access to and utilization of eye care services in Ghana. *Int. J. Heal. Res.* 2013;6(3):7-15.
3. Sheppard AL, Davies LN. Clinical evaluation of the Gran Seiko Auto Ref/Keratometer WAM-5500. Ophthalmic Physiol. Opt. 2010;30(2):143-151.
4. Shneor E, Millodot M, Avraham O, Amar S, Gordon-Shaag A. Clinical evaluation of the L80 autorefractometer. *Clin. Exp. Optom.* 2012;95(1):66-71.
5. Rabbetts RB. *Clinical Visual Optics*. 4th ed. Butterworth-Heinemann; 2007.
6. MacKenzie GE. Reproducibility of sphero-cylindrical prescriptions. *Ophthalmic Physiol. Opt.* 2008;28(2):143-150.
7. Rosenfield M, Chiu NN. Repeatability of Subjective and Objective Refraction. *Optom. Vis. Sci.* 1995;72(8):577-579.
8. *Optometric Clinical Practice Guideline. Care of the Patient with Myopia. American Optometric Association.*; 2006.
9. *Optometric Clinical Practice Guideline. Care of the Patient with Hyperopia. American Optometric Association.*; 2007.
10. Elliot DB. *Clinical Procedures in Primary Eye Care.* 4th ed. Saunders W.B.; 2014.
11. Ciuffreda KJ, Rosenfield M. Evaluation of the SVOne: A handheld, smartphone-based autorefractor. *Optom. Vis. Sci.* 2015;92(12):1133-9.
12. Sanfilippo PG, Chu B, Bigault O, et al. What is the appropriate age cut-off for cycloplegia in refraction? *Acta Ophthalmol.* 2014;92:458-462.
13. Kinge B, Milelfart A, Jacobsen G. Clinical evaluation of the Allergan Humphrey 500 autorefractor and the Nidek AR-100 autorefractor. *Br. J. Ophthalmol.* 1996;80:35-39.
14. Pujol J, Ondategui-Parra JC, Badiella L, Otero C, Vilaseca M, Aldaba M. Spherical subjective refraction with a novel 3D virtual reality based system. *J. Optom.* 2016.
15. Otero C, Vilaseca M, Arjona M, Martínez-Roda J a., Pujol J. Repeatability of Aberrometric Measurements With a New Instrument for Vision Analysis Based on Adaptive Optics. *J. Refract. Surg.* 2015;31(3):188-194.
16. James S, Schanz P, Bullimore M. Evaluation of an automated subjective refractor. *Optom. Vis. Sci.* 2004;81(5):334-340.
17. Dave T, Fukuma Y. Clinical evaluation of the Topcon BV-1000 automated subjective refraction system. *Optom. Vis. Sci.* 2004;81(5):323-33.
18. Villegas EA, Alcón E, Artal P. Minimum amount of astigmatism that should be corrected. *J. Cataract Refract. Surg.* 2014;40(1):13-19.