Title: Validation of a novel objective method for the qualitative and quantitative assessment of binocular accommodative facility

Running head: A novel method for the assessment of BAF

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Disclosure: The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article**.**

Acknowledgments: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors**.** The authors thank all the participants who selflessly collaborated in this research and Servilens Fit & Covers Company (Granada, Spain) for the donation of the contact lens supplies used in this study.

Abstract

Purpose: Assessing binocular accommodative facility (BAF) enables the evaluation of the interaction between the accommodative and vergence systems, which is relevant for the diagnosis of accommodative and binocular disorders. However, the tests used to assess BAF present methodological caveats (e.g., lack of objective control, vergence demands and image size alterations), limiting its external validity. This study aimed to (i) develop a new objective method to quantitatively and qualitatively evaluate the BAF in free-viewing conditions, and explore its validity by the comparison with the Hart Chart test, and (ii) assess the inter-session reliability of the proposed method.

Methods: 33 healthy young adults (mean age ± SD = 22.04 ± 2.49 years) took part in this study. We used a binocular open-field autorefractor to continuously assess the magnitude of accommodative response during a 60-sec period, while participants repeatedly changed fixation from a far to a near chart when clarity of vision was achieved at one level. Accommodative response data were used to calculate the quantitative (number of cycles) and qualitative (percentage of incorrect times accommodating or dis-accommodating and the magnitude of the accommodative change).

Results: Our data revealed that the new proposed method accurately counted the number of cycles per minute when compared with the Hart Chart test ($p = 0.23$, ES = 0.02; mean difference = 0.18 ± 0.85). The inter-session reliability of the proposed method was demonstrated to be excellent (Pearson r and intraclass correlation coefficient: 0.95 to 0.98) for the parameters obtained with the BAF test.

Conclusions: The present outcomes evidence that the proposed objective method allows to accurately assess the BAF in a qualitative and quantitative manner by the combination of the classical Hart chart test and a binocular open-field autorefractometer. Our findings may be of relevance for the diagnosis and treatment of accommodative and binocular disorders.

Introduction

Accommodative facility is a clinical test used to evaluate the ability of the visual system to alter accommodation rapidly and accurately when the dioptric stimulus to accommodation is situated between two different levels. Accommodative facility can be evaluated in monocular and binocular testing, providing a direct evaluation of the dynamics of accommodative response, and additionally the binocular accommodative facility (BAF) procedure reflects the interactive nature of the accommodation-vergence relation.[1] Indeed, BAF can be used as a predictor of visual discomfort,[2,3] diagnostic sign for accommodative and binocular disorders,[4–7] and together with the accommodative response as an independent predictor of myopia progression.[8,9]

The clinical standard for accommodative facility testing was described by Zellers and Alpert[10], in which the accommodation level is changed with the use of a lens flipper (usually ± 2.00 D). During this procedure, when sharp vision is achieved at one level, the lens is flipped to provoke accommodation to the other level. The number of cycles between both levels in a given time period, usually one minute, is recorded. This method suffers from a significant variation in response times due to the time taken to change the lenses by the subjects, together with the examiner's reaction and motor times if the lenses are not changed by themselves.[11] Another, more natural alternative, is the Hart chart test, a method commonly used in the training of accommodative facility and saccades.[12–14] The patient changes fixation from a standard distance visual acuity chart to a near acuity chart and he/she is instructed to report when the fine detail on each chart appears both clear and single. The numbers of times this happens during a 60-s period is recorded. However, both methods are subjective in nature since the result depends on subject's criteria for judging when the target is clear or blurry and subject's reaction times to respond to blur.[11] The inter-individual subjective variability, the assessment of BAF in certain populations who may find difficult to understand this procedure (e.g., preschool children[15]), a lack of homogenous conditions of testing,[1] and the different dynamics of BAF found between refractive groups[11] have caused significant variation in the reported values of BAF in the clinical literature,[10,16–18] and therefore challenge the reliability and validity of this measure.[18]

To date only a single work has tested the BAF through the combination of objectives (the monocular estimation method retinoscopy) and subjective (± 2.00 D lens flipper) techniques.[19] Despite the fact that 86% agreement was found between these techniques, this method requires to perform previous tests to predict when the target is blurred and also requires a very laborious procedure for data analysis and interpretation. Remarkably, the use of flippers to assess BAF presents certain limitations, since the use of lenses vary the vergence demands and modify the retinal image size, which may alter the accommodative and vergence responses.[20,21] In addition, the sensitivity of the classical objective techniques (e.g., monocular estimation method retinoscopy or Nott dynamic retinoscopy) to measure the accommodative function is limited (0.25 diopters [D]) and it is highly dependent on the experimenter.[22,23]

The relatively recent incorporation of binocular open-field autorefractometers has allowed to obtain more reliable measures of static and dynamic accommodation.[23–26] Its applied interest is double, as it permits measuring the accommodative response while viewing real targets at any distance (open-field) and also, allows to keep both eyes open during recording (binocular).[25] The objective determination of accommodative responses while shifting gaze from far distance to 40 cm (i.e., the distances established to assess the accommodative facility) allows to verify the accuracy in both the accommodation and dis-accommodation levels, as well as to determine the number of correctly completed cycles. In view of this, we consider that the objective measure of accommodative facility, using a binocular open field autorefractometer, in synchrony with the subjective accommodative facility measured with Hart charts, might help to alleviate the issues of measuring BAF to date. This objective method permits the elimination of the factors previously mentioned (i.e., individual judgment for clarity of vision, limited test sensitivity, non-naturalistic conditions, monocular measurement) associated to subjective testing or available techniques, and therefore could be considered as a new objective method to assess BAF.

Here, we investigated the validity of measuring binocular accommodative facility using the Hart charts in conjunction with the Grand Seiko Auto Ref/Keratometer WAM-5500 (Grand

Seiko Co. Ltd., Hiroshima, Japan) in young participants. The main objectives of the present study were: (1) to propose a new objective method to assess the BAF in both qualitative (number of cycles) and quantitative (percentage of incorrect times accommodating or dis-accommodating, and amplitude of accommodation) terms, and (3) to assess the inter-session repeatability of the proposed method by analysing two measurements on different days under identical experimental conditions.

Methods

Ethical approval and study subjects

The present study followed the tenets of the Declaration of Helsinki and was approved by the Granada University Ethical Committee. All participants gave informed consent before their enrollment in this investigation. Forty university students took part in this investigation. For inclusion in the present study, all participants were free of any ocular or systemic disease. In addition, they were screened by a board certified optometrist, and the following inclusion criteria were considered: 1) at least 0.0 log MAR corrected visual acuity in both eyes, 2) having a corrected refractive error between -5.00 D and +3.00 D, as well as ≤1.5 D of astigmatism in either eye, 3) no anisometropia ≥ 2.00 D, 4) had no history of refractive surgery and orthokeratology, 5) stereopsis ≤ 40” with no history of strabismus and amblyopia treatment, 6) be free of any accommodative and binocular dysfunction following the recommendations of Scheiman and Wick (2008) or history of having been treated of them, 7) scoring ≤ 24 on the Conlon Survey which assesses visual discomfort,[27] and < 21 at the Convergence Insufficiency Symptom Survey (CISS),[28] 8) no present accommodative lag ≥ 1.55 D at 20 cm, which represent the normal level of tonic accommodation,[29] 9) not taking medications known to alter accommodation, and 10) score a value < 3 with the Stanford Sleepiness Scale (SSS) to ensure an appropriate level of alertness.[30]

After screening, seven participants were excluded from further analysis: one presented a lag of accommodation higher to 1.55 D at 20 cm, three had a myopic refractive error > 5.00 D, one individual reported a value higher than 3 using the SSS before the commencement of the main experimental session, and two did not complete the entire experiment. As a result, 33 university students were enrolled in the study (mean age ± SD = 22.04 ± 2.49 years, 20 females). The mean spherical equivalent refractive error was -0.65 ± 0.95 D (range -2.91 to 0.89 D). All participants were asked to avoid alcohol consumption, any practice of vigorous exercise 6 h before each experimental session, to sleep for at least 7 h and to not consume caffeinated beverages or other stimulants in the 3 h prior to testing.

Procedure

Four sessions in different days were conducted for this study. Participants received written information about the study, and were informed about their right to leave the experiment at any moment. All experimental sessions were scheduled at the same time of the day (± 1 hour), and separated by a minimum of 24 hours and a maximum of 72 hours. In the first visit, both a biomicroscopy and a direct ophthalmoscopy examination were performed in order to detect any ocular disease. An auto Ref/Keratometer (WAM-5500, Grand Seiko Co. Ltd., Hiroshima, Japan) was used to obtain objective ocular refraction and keratometry. Three readings were taken in each eye and averaged. Then, a monocular and binocular subjective refraction using an endpoint criterion of maximum plus consistent with best vision was performed. At this point, soft contact lenses (SCLs) were ordered to the manufacturer (Servilens Fit & Covers Company, Granada, Spain) based on the refractive and keratometric assessment and adjusted for the vertex distance of each individual. Disposable HEMA and Ocufilcon D (55% water content) soft contact lenses were used. When a lower 0.75D astigmatism was found, soft contact lenses with appropriate spherical equivalent were selected and toric soft contact lenses were used to compensate astigmatism ≥ 0.75D. For screening purposes, we also measured the accommodative response at 20 cm with the WAM-5500, since lags of accommodation greater than 1.55 D at this distance were considered as exclusion criteria.

In the second session, SCLs were individually fitted. This procedure was performed in order to avoid the possible influence of vertex distance (e.g., spectacles vs. SCL) on accommodative demand. A SCL fitting evaluation and an over-refraction were performed after participants wore the soft contact lenses during one hour. An appropriate SCL centred and movement, and a distance visual acuity ≤ 0.00 log MAR in each eye, were required to establish participation in the current study. Lastly, accommodative and binocular function were evaluated, following the recommendations of Scheiman and Wick[7]. This session allowed us to further screen participants in order for them to meet the inclusion criteria.

In the third session, participants were asked to wear the SCL for at least one hour before they attended to the lab. The examiner explained the procedure to assess the accommodative facility. The binocular accommodative response at distance (5 m) and near (40 cm) was recorded during 60-s at each distance while wearing their individually fitted SCL. Also, the BAF test (see below for a detailed explanation of the BAF measure) was carefully explained to participants, and subsequently, they performed the test. In addition, they were asked to alter their accommodation between the far and near targets (approximately 6-8 cycles) in order to ensure an appropriate alignment of the patient with both targets (near and far) and the autorefractometer, as well as to confirm a correct understanding of the test. It should be noted that data from one participant were lost because of data recording failure, and thus, this subject was discarded from further reliability analyses (see below).

The fourth visit to the laboratory was considered as the main experimental session, in which the binocular accommodative response at distance (5 m) and near (40 cm) over a 60-sec period was measured, and also the BAF test was performed. Data from this session were considered for the comparison of this method against the Hart chart test (objective 1) whereas both BAF assessments (session 3 and 4) were considered for reliability analyses (objective 2).

Accommodative response measurement

Accommodative response measurements were taken with the Grand Seiko WAM-5500 open-field auto-refractor (Grand Seiko Co. Ltd., Hiroshima, Japan) in Hi-Speed mode, which permits a dynamic recording of refraction and pupil size at a rate of ~ 5 Hz, with a sensitivity of 0.01 D and 0.1 mm, respectively. The WAM-5500 has been repeatedly shown to be reliable and accurate in the dynamic accommodation measurements.[25,31] For all measures, participants were asked to position their chin and forehead on the respective supports, and viewed a target in front of their eyes (~ 6/9 letter size) through the open-field beam-splitter at distance (5 m) and near (40 cm) during 60-s. These values were further used to analyze the accuracy of the BAF.

Binocular accommodative facility measurements

A schematic illustration of the experimental set up is depicted in Figure 1 (panel A). Hart charts for distance and 40 cm, with a letter size of 11.2 mm (0.19 log MAR) and 0.9 mm (0.19 log MAR) for the far and near charts, respectively, were used to measure BAF.[7] The luminance of charts was 42.7 cd/m^2 and 44.2 cd/m^2 for the far and near charts, respectively, and the font type used was Helvetica (capital letters). Participants were asked to alternatively focus between a distance (5 m) Hart chart of high contrast (90%) mounted at eye level and a near (40 cm) Hart chart of high contrast (90%) placed slightly inferiorly, both being positioned along the midline. Subjects were asked to focus one letter from the distance Hart chart, and then shift their focus to the near Hart chart and focus one letter, and so forth. Participants did not have to name the letters during the BAF test, although, they were continuously asked to make sure that letters appear sharp before shifting their gaze to the other distance. The number of cycles completed in 60-s under binocular viewing conditions were counted by an examiner in order to test the reliability of the new proposed method. Each change constituted a half cycle and two consecutive changes a full cycle. A custom-made target was used for the near chart, which was located at 40 cm using the ruler attached to the upper part of the autorefractor. This near chart allowed subjects to look at the far target without obstructing the participant´s view and with minimal vertical movement of the eyes (see figure 1, panel B).

The objective measurements of BAF were obtained using the WAM-5500, which dynamically monitored the refractive error during the facility measurements. The AR measurements with the autorefractor were started in synchrony with participants initiating the BAF test. The start button on the autorefractor produced a “beep” which indicated the commencement of the test to the participants. This procedure was very similar to the one used by Allen et al.,[32], aimed to reduce the variability between the moment of objective recording and when the participants started. Although subjects viewed both targets binocularly, AR measures were only obtained from the sighting dominant eye (determined by the hole-in-card method) at the time (right eye dominance was observed in 22 out of 33 participants).[33] During the dynamic measurements, the examiner ensured that the instrument remained carefully aligned. Room illumination conditions were maintained at ~150 lux (Illuminance meter T-10, Konica Minolta, Inc., Tokyo, Japan) during the entire experimental session.

Data processing and statistical analysis

By interfacing with a PC running the WAM communication system (WCS-1) software, the instrument registers the dynamic data to a Microsoft Excel file approximately every 200 milliseconds. Blinks or recording errors were identified as missing data and eliminated. All those AR values varying more than 3 standard deviations from the AR mean were considered as outliers and were removed from further analysis.[31,34] Baseline accommodative response was calculated by subtracting the mean value from the dynamic measures and the baseline static refractive value obtained in far distance to the accommodative demand at each distance (0 and 2.5 D).[35] Baseline AR measurements (mean ± standard deviation) for each distance was used as reference value to analyze AR accuracy in each accommodation level and to evaluate the frequency of accommodative changes over the one minute task.

For the quantitative and qualitative analysis of BAF, we first count the zero-crossings of the accommodation measurement signal to estimate an approximate frequency. We then fit the signal with a sinusoid at that frequency, with amplitude and phase as free parameters using the

Levenberg-Marquardt damped least-squares method.[36] The accommodation signal is then cleaned-up, as we did for the near and far baseline measurements, by removing in-transit measurements: all measurements taken as the eye's crystalline lens power was shifting from far to near and back, i.e., those measurements smaller or larger than the near and far baseline measurements ± 3 SDs. Finally, the similarity of the accommodation measurement signal and the fitted sinusoid, is validated by cross-correlating the cleaned-up signal with the fitted sinusoid. A normalized cross-correlation score > 0.8 indicated a good fit.

To evaluate the reliability between the numbers of cycles obtained by the proposed novel method and the classical method (count the number of changes from far to near), we first performed a t-test for related samples to determine possible differences between methods, and the standardized difference (Cohen´s d effect size [ES]) was used to interpret the magnitude of the change. The interpretation of the ES followed established criteria: <0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, 1.2–2.0 = large, and >2 = very large.[37] If the differences were insignificant, we calculated the Pearson product moment correlation coefficient (Pearson r), the intraclass correlation coefficient (ICC) and the coefficient of variation (CV) with their corresponding 95% confidence interval (95% CI) to test reliability.[38] Lastly, to assess the level of agreement, we calculated the mean difference between both methods using the Bland and Altman test.[39]

Additionally, the reliability of the proposed method was assessed by the analysis of two identical experimental sessions (sessions 3 and 4). The possible differences between both BAF measurements were tested by related samples t-tests, which were interpreted according to the magnitude of the change (see above for a description). Subsequently, reliability indices (Pearson r, ICC, and CV) were obtained for each dependent variable (number of cycles, mean magnitude of accommodative change [i.e., difference in accommodative response between the far and near targets], and accuracy of the accommodative system to either accommodate or dis-accommodate). The level of agreement between both measurements for each BAF parameter (number of cycles, mean magnitude of accommodative change, and accuracy of the accommodative system to either accommodate or dis-accommodate) was calculated by the Bland and Altman test.

Results

Table 1 shows the descriptive values of the number of cycles, the percentage of incorrect cycles of accommodation and dis-accommodation, and the mean magnitude of accommodative change between the far and near targets obtained for the new proposed method in both experimental sessions. An example of the fitted sinusoid and the AR values obtained from one subject is presented in Figure 2.

The first set of analyses to determine the reliability of both methods indicates that the difference between them was statistically insignificant ($p = 0.23$, ES = 0.02), with 26.42 ± 8.19 cycles-per-minute (cpm) for the classical Hart Chart test and 26.33 ± 8.34 cpm for the new proposed method. Both methods were highly comparable since the level of correlation was Pearson r (95% CI) = 0.99 (0.99-1), ICC (95% CI) = 1 (0.99-1), and CV (95%CI) = 2.00 (1.54-2.86). The Bland and Altman method is displayed in Figure 3, and it indicates that the mean difference between both methods is 0.11 ± 0.85 (95% CI: -1.56 to 1.78) cpm.

Lastly, we assessed the repeatability of the new proposed method by the analysis of two identical experimental sessions (Table 1). Our analysis indicated that the BAF test exhibits excellent reliability for the different parameters of the proposed method, since the reliability indices (Pearson r and ICC) ranged between 0.95 and 0.98. The analysis of the level of agreement between both BAF measurements indicated that the mean difference between both methods is -0.13 ± 2.50 (95% CI: -4.77 to 5.13) cpm for the number of cycles with the BAF test, -0.31 ± 2.47 (95% CI: -5.15 to 4.53) cpm for the number of cycles with the Hart chart test, 1.99 ± 10.26 (95% CI: -18.1 to 22.1) % for the percentage of cycles under-relaxed, 4.08 ± 9.85

(95% CI: -15.2 to 23.4) % for the percentage of cycles under-accommodated, and -0.02 ± 0.05 D for the mean magnitude of accommodative change.

Discussion

The present study aimed to develop a new objective method to obtain both quantitative and qualitative indices of the binocular accommodative response. Our data demonstrated that: (1) the new proposed method allows to count the number of cycles per minute, and these values are highly comparable with those obtained by the classical Hart chart test, and (2) the proposed method has demonstrated to be highly repeatable for the number of cycles per minute, the percentage of times incorrectly accommodated and dis-accommodated, and the mean magnitude of accommodative change.

Accommodative facility has normally been evaluated by using flipper lenses or Hart charts, however each method presents advantages and disadvantages based on their particular characteristics (e.g., use of lenses, conditions of measurement, participant´s reaction time, etc).[17] Indeed, the differences between both methods are evident, the flipper lenses method modulates the accommodative demand by positive and negative lenses (normally ± 2.00 D) and maintains a constant stimulus distance. Based on this method, Radhakrishnan et al.,[11] and Allen et al.,[32] objectively evaluated the accommodative facility by the synchronization of automated flippers with objective measurements of dynamic accommodation response. However, this method is not free of caveats. Importantly, the use of lenses modify vergence demands and retinal image size,[20,21] and the flipper requires reaction and motor responses (flip lenses or press the button) to change lenses. Recently, Otero and colleagues[40] have developed an automated system to assess accommodative facility, which aims to avoid the delays in flipping the lens, with the use of a focus-tunable lens. But again, vergence demands and retinal image sizes are affected by the use of the lens. On the other hand, the Hart chart method permits the assessment of accommodative facility in a more ecologically valid way, since it is performed in free-viewing conditions and the accommodative demands are only modified by the change of the stimulus distance.[14] However, the main limitation of this method is the lack of objective control on the accuracy of accommodative facility, in other words, it does not allow assessing whether the magnitude of accommodation and dis-accommodation corresponds to the accommodative demands at far (0.20 D at 5 m) and near (2.5 D at 40 cm). This fact limits the reliability of accommodative facility, and the only way to obtain a valid and reliable measure of accommodative facility would be to objectively monitor the accommodative response during the Hart chart test in naturalistic viewing conditions. Our method shows that accommodative facility can be objectively measured, and allows a valid evaluation of BAF in quantitative terms (number of cycles per minutes), as demonstrated to yield very similar values to those obtained by the classical Hart chart method (0.71%: mean difference between methods [95% CI] = 0.18 [-1.49 to 1.85] cpm). In addition, the objective monitoring of accommodative response during the accommodative facility test allows to assess the qualitative characteristics (accuracy of accommodation and dis-accommodation, and mean magnitude of accommodative change) of the BAF.

The concept of repeatability refers to the precision in repeated measurement of any apparatus when all external factors are assumed constant.[41] Importantly, the assessment of physiological indices is subject to multiple sources of variability, with high levels of repeatability being of paramount relevance for the usefulness of any method or device. In the present study, we found that the inter-session repeatability of the BAF test is excellent (see Table 1), and thus, two measures of this method can be considered reliable in qualitative and quantitative terms. Taken together, our results evidence that the proposed method allows to obtain objective, valid and repeatable measurements of BAF, enabling the assessment of the ability of the visual system to alter accommodation between far and near targets in a quantitative and qualitative manner.

There is accumulated evidence on the influence of refractive error on ocular accommodation.[9,42,43] In particular, myopes show a lower number of cycles per minute in accommodative facility testing with semi-automated flippers,[11] however, this test is not sensitive enough to accurately differentiate between myopes and non-myopes.[44] A growing area of research is focused on myopia progression, and a reduced rate of accommodative facility has been identified as an independent factor of myopia progression in young adults.[9] In the current study, our experimental sample was formed by healthy young adults with a small range of refractive error, and thus, we were not able to test the influence of refractive error on the quantitative and qualitative indices of accommodative facility. We hope that future studies will consider testing the possible differences between groups with refractive errors on BAF. Also, qualitative characteristics of accommodative facility may be considered as a possible sign of altered visual function. The inclusion of individuals diagnosed with various visual dysfunctions in a future study would allow to assess the ability of the test (sensitivity) to correctly identify individuals with certain binocular or accommodative dysfunction

Limitations and potential strengths

There are several circumstances that may limit the implementation of the new proposed method. First, we consider that this method could be of interest in research and clinical settings, however, the relatively high cost of this instrument may limit its use by clinicians. Future research should focus on the development of cost-effective instruments that would allow to objectively assess BAF. Second, this study has been carried out with healthy young adults, demonstrating an acceptable level of validity and inter-session reliability. Nevertheless, future studies should explore the accuracy and repeatability of this method in clinical and pediatric populations, since accommodative-vergence function may be altered or test instructions can be difficult to understand, respectively. Third, the relevance of refractive error on the BAF have been approached in several studies,[8,11,44] the limited range of refractive errors included in this study did not allow us to obtain solid conclusions in this regard. It is our hope that future studies will consider an experimental sample with larger refractive errors, and explore the influence of refractive error on quantitative and qualitative characteristics of BAF. Fourth, we used a determined letter size (0.19 log MAR; 20/31 Snellen), and the use of other letter sizes may lead to different results in the BAF test. The mediating role of letter size should be addressed in future investigations. Lastly, as cycle period usually changes during the progression of a measurement session, the single signal frequency determined by the fitting procedure for the entire time series may seem sub-optimal when considered separately for smaller intervals, e.g. for the first ten seconds. However, cross-correlation of the measurement and fitted signals establishes that the fitting error for the entire measurement signal is kept at a minimum.

Importantly, this method would permit to evaluate the accommodative facility in binocular and free-viewing conditions, without the use of optical lenses that are known to vary vergence demands and retinal image size.[20,21] Also, it would constitute a progressive shift from far to near distances (no abrupt changes induced by flipper lenses), and eliminate reaction and motor times (either from the patient or examiner depending on the methodology).[11,44] We believe that this method could be of special relevance for the control of visual therapy programs, which are focused on the enhancement of the BAF, as in the case of clinical populations and athletes.[12,14]

A practical guide to measure BAF

To assess the BAF with the new proposed method:

1. To obtain participant´s refractive error at far, using the static mode of WAM-5500.
2. To assess dynamic binocular accommodative response at far (5 m) during 1 minute, and subsequently, the same procedure at 40 cm.
3. To perform the BAF test after incorporating the near target for accommodative facility testing (see figure 1, panel B), using the WAM-5500 device. After it, to check that the near target is slightly below to the far target, and both targets can be alternatively viewed.
4. At this point, data (static value of refractive error at far, both files of dynamic accommodative response at far and near, and the file of BAF testing) must be implemented into the available MATLAB code. Due to a submitted patent application

(IPR-725) the source code will be released without restriction at a later date in Digibug (UGR institutional repository).

5. The values of number of cycles per minute, number of cycles incorrectly accommodated and dis-accommodated, as well as the mean magnitude of the accommodative change over the 1-minute period are given.

CONCLUSIONS

A new objective method to evaluate the accuracy of binocular accommodative facility by combining the Hart chart test with dynamic monitoring of accommodative response is proposed, which has been demonstrated to be valid when compared with the Hart chart test, and repeatable by analysing inter-session reliability. Our results indicate that this method permits to automatically count the number of cycles per minute, and also, assess the binocular accommodative facility in qualitative terms, enhancing actual testing procedures. The present study could help for a more accurate assessment of binocular accommodative facility, which may be of relevance in the control of visual training (e.g., clinical populations and athletes), in the diagnosis of different accommodative and binocular disorders, as well as a possible indicator of myopia progression. Future studies are guaranteed in this regard.

References

1. Siderov JJA. The importance of the test parameters in the clinical assessement of accommodative facility. Optom Vis Sci. 1990;67(7):551–7.
2. Kiely PM, Crewther SG, Crewther DP. Is there an association between functional vision and learning to read? Clin Exp Optom. 2001;84(6):346–53.
3. Wick B, Gall R YT. Clinical testing of accommodative facility: part III. Masked assessment of the relation between visual symptoms and binocular test results in school children and adults. Optometry. 2002;73(3):173–81.
4. Levine S , Ciuffreda KJ , Selenow A FN. Clinical assessment of accommodative facility in symptomatic and asymptomatic individuals. J Am Optom Assoc. 1985;56(4):286–90.
5. Lara F, Cacho P, García a, Megías R. General binocular disorders: prevalence in a clinic population. Ophthalmic Physiol Opt [Internet]. 2001 Jan;21(1):70–4. Available from: http://www.ncbi.nlm.nih.gov/pubmed/11220042
6. García A, Cacho P, Lara F, Megías R. The relation between accommodative facility and general binocular dysfunction. Ophthalmic Physiol Opt. 2000;20(2):98–104.
7. Scheiman M, Wick B. Clinical management of binocular vision: heterophoric, accommodative, and eye movement disorders. Lippincott Williams & Wilkins; 2008.
8. O'Leary DJ, Allen PM. Facility of accommodation in myopia. Ophthalmic Physiol Opt. 2001;21(5):352–5.
9. Allen PM, O´Leary DJ. Accommodation functions: Co-dependency and relationship to refractive error. Vision Res. 2006;46(4):491–505.
10. Zellers JA , Alpert TL RM. A review of the literature and a normative study of accommodative facility. J Am Optom Assoc. 1984;55(1):31–7.
11. Radhakrishnan H, Allen PM, Charman WN. Dynamics of accommodative facility in myopes. Investig Ophthalmol Vis Sci. 2007;48(9):4375–82.
12. Quevedo L, Solé J, Palmi J, Planas A, Saona C. Experimental study of visual training effects in shooting initiation. Clin Exp Optom. 1999;82(1):23–8.
13. Zupan MF, Arata AW, Wile A, Parker R. Visual adaptations to sports vision enhancement training. A study of collegiate athletes at the US Air Force Academy. Optom Today UK. 2006;43–8.

14. Vasudevan B, Ciuffreda KJ, Ludlam DP. Accommodative training to reduce nearwork-induced transient myopia. Optom Vis Sci [Internet]. 2009 Nov;86(11):1287–94. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19786929

15. Scheiman M, Herzberg H, Frantz K MM. Normative study of accommodative facility in elementary schoolchidren. J Optom Physiol Opt. 1988;65(2):127–34.

16. Jiménez R, González MD, Pérez MA, Garcia JA. Evolution of accommodative function and development of ocular movements in children. Ophthalmic Physiol Opt. 2003;23(2):97–107.

17. Wick B, Yothers TL, Jiang BC MS. Clinical testing of accommodative facility: Part 1. A critical appraisal of the literature. Optometry. 2002;73(1):11–23.

18. Yothers T, Wick B MS. Clinical testing of accommodative facility: part II. Development of an amplitude-scaled test. Optometry. 2002;73(2):91–102.

19. Gallaway M SM. Assessment of accommodative facility using MEM retinoscopy. J Am Optom Assoc. 1990;61(1):36–9.

20. McLin LN, Schor CM, Kruger PB. Changing size (looming) as a stimulus to accommodation and vergence. Vision Res. 1988;28(8):883–98.

21. Hunt OA, Wolffsohn JS, García-Resúa C. Ocular motor triad with single vision contact lenses compared to spectacle lenses. Contact Lens Anterior Eye. 2006;29(5):239–45.

22. Antona B, Sanchez I, Barrio A, Barra F, Gonzalez E. Intra-examiner repeatability and agreement in accommodative response measurements. Ophthalmic Physiol Opt. 2009;29(6):606–14.

23. McClelland JF, Saunders KJ. The repeatability and validity of dynamic retinoscopy in assessing the accommodative response. Ophthalmic Physiol Opt. 2003;23(3):243–50.

24. Win-Hall DM, Houser J, Glasser A. Static and Dynamic Measurement of Accommodation Using the Grand Seiko WAM-5500 Autorefractor. Optom Vis Sci. 2010;87(11).

25. Sheppard AL, Davies LN. Clinical evaluation of the Grand Seiko Auto Ref/Keratometer WAM-5500. Ophthalmic Physiol Opt [Internet]. 2010 Mar [cited 2015 Feb 16];30(2):143–51. Available from: http://www.ncbi.nlm.nih.gov/pubmed/20444118

26. Aldaba M, Gómez-López S, Vilaseca M, Pujol J, Arjona M. Comparing Autorefractors

for Measurement of Accommodation. Optom Vis Sci. 2015;92(10).

27. Conlon EG, Lovegrove WJ, Chekaluk E, Pattison PE. Measuring Visual Discomfort. Vis cogn [Internet]. 1999 Dec 1;6(6):637–63. Available from: http://dx.doi.org/10.1080/135062899394885

28. Rouse MW, Borsting EJ, Mitchell GL, Scheiman M, Cotter S a, Cooper J, et al. Validity and reliability of the revised convergence insufficiency symptom survey in adults. Ophthalmic Physiol Opt [Internet]. 2004 Sep;24(5):384–90. Available from: http://www.ncbi.nlm.nih.gov/pubmed/15315652

29. Wang B, Ciuffreda KJ. Depth-of-focus of the human eye in the near retinal periphery. Vision Res. 2004;44:1115–25.

30. Hoddes E, Zarcone V, Dement W. Development and use of Stanford Sleepiness scale (SSS). Psychophysiology. 1972;9(1):150.

31. Tosha C, Borsting E, Ridder WH, Chase C. Accommodation response and visual discomfort. Ophthalmic Physiol Opt [Internet]. 2009 Nov [cited 2014 Jul 2];29(6):625–33. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19821926

32. Allen PM, Charman WN, Radhakrishnan H. Changes in dynamics of accommodation after accommodative facility training in myopes and emmetropes. Vision Res [Internet]. 2010;50(10):947–55. Available from: http://dx.doi.org/10.1016/j.visres.2010.03.007

33. Momeni-Moghaddam H, McAlinden C, Azimi A, Sobhani M, Skiadaresi E. Comparing accommodative function between the dominant and non-dominant eye. Graefe's Arch Clin Exp Ophthalmol. 2014;252(3):509–14.

34. Vera J, Diaz-Piedra C, Jim??nez R, Morales JM, Catena A, Cardenas D, et al. Driving time modulates accommodative response and intraocular pressure. Physiol Behav. 2016;

35. Poltavski D V., Biberdorf D, Petros T V. Accommodative response and cortical activity during sustained attention. Vision Res [Internet]. 2012;63:1–8. Available from: http://dx.doi.org/10.1016/j.visres.2012.04.017

36. Moré J. The Levenberg-Marquardt algorithm: Implementation and theory. In: Heidelberg, editor. Numerical analysis [Internet]. Berlin: Springer; 1978. p. 105–16. Available from: http://link.springer.com/10.1007/BFb0067700

37. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009;41(1):3–12.

38. Vaz S, Falkmer T, Passmore AE, Parsons R, Andreou P. The Case for Using the Repeatability Coefficient When Calculating Test-Retest Reliability. PLoS One. 2013;8(9):1–7.

39. Martin Bland J, Altman D. Statistical Methods for Assessing Agreement Between Two Methods of Clinical Measurement. Lancet. 1986;327(8476):307–10.

40. Otero C, Aldaba M, López S, Díaz-Doutón F, Vera-Díaz FA, Pujol J. Random Changes of Accommodation Stimuli: An Automated Extension of the Flippers Accommodative Facility Test. Curr Eye Res [Internet]. 2018;0(0):1–8. Available from: https://doi.org/10.1080/02713683.2018.1444181

41. McAlinden C, Khadka J, Pesudovs K. Statistical methods for conducting agreement (comparison of clinical tests) and precision (repeatability or reproducibility) studies in optometry and ophthalmology. Ophthalmic Physiol Opt. 2011;31(4):330–8.

42. Millodot M. The effect of refractive error on the accommodative response gradient: A summary and update. Ophthalmic Physiol Opt. 2015;35(6):607–12.

43. Maiello G, Kerber KL, Thorn F, Bex PJ, Vera-Diaz FA. Vergence driven accommodation with simulated disparity in myopia and emmetropia. Exp Eye Res [Internet]. 2017;166(November 2016):96–105. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0014483516304183

44. Pandian A, Sankaridurg PR, Naduvilath T, O'Leary D, Sweeney DF, Rose K, et al. Accommodative facility in eyes with and without myopia. Investig Ophthalmol Vis Sci. 2006;47(11):4725–31.

Figure captions

Figure 1. Experimental set up. In panel A) is displayed a schematic illustration of the binocular accommodative facility procedure, and in panel B) is shown the near target, which permits to alter the viewing distance between the near and far charts.

Figure 2. A graphical illustration of the binocular accommodative facility from one subject. In the current example, the mean magnitude of accommodative change is 2.58D and the number of cycles is 16.

Figure 3. Bland and Altman plots illustrating the level of agreement between the new proposed method and the classical Hart chart test for the number of cycles per minute. The dotted lines represent the mean bias and the dashed lines show the 95% limits of agreement. The regression line is represented by a solid black line, and the grey lines indicate the value zero.

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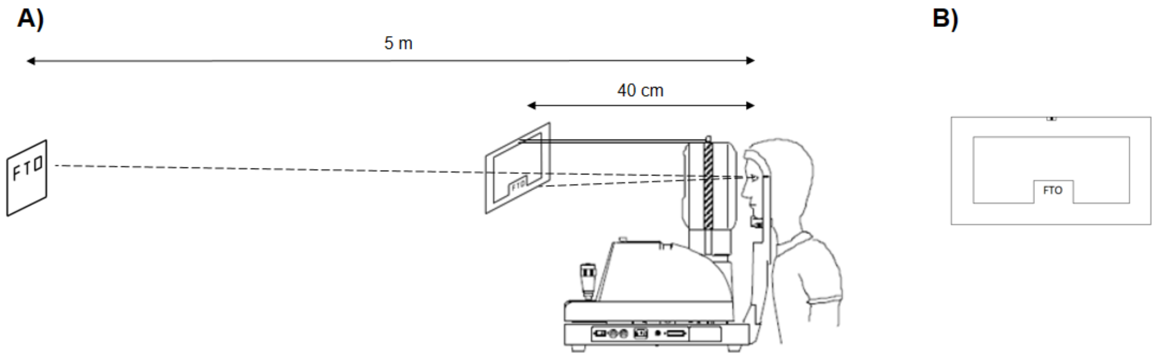

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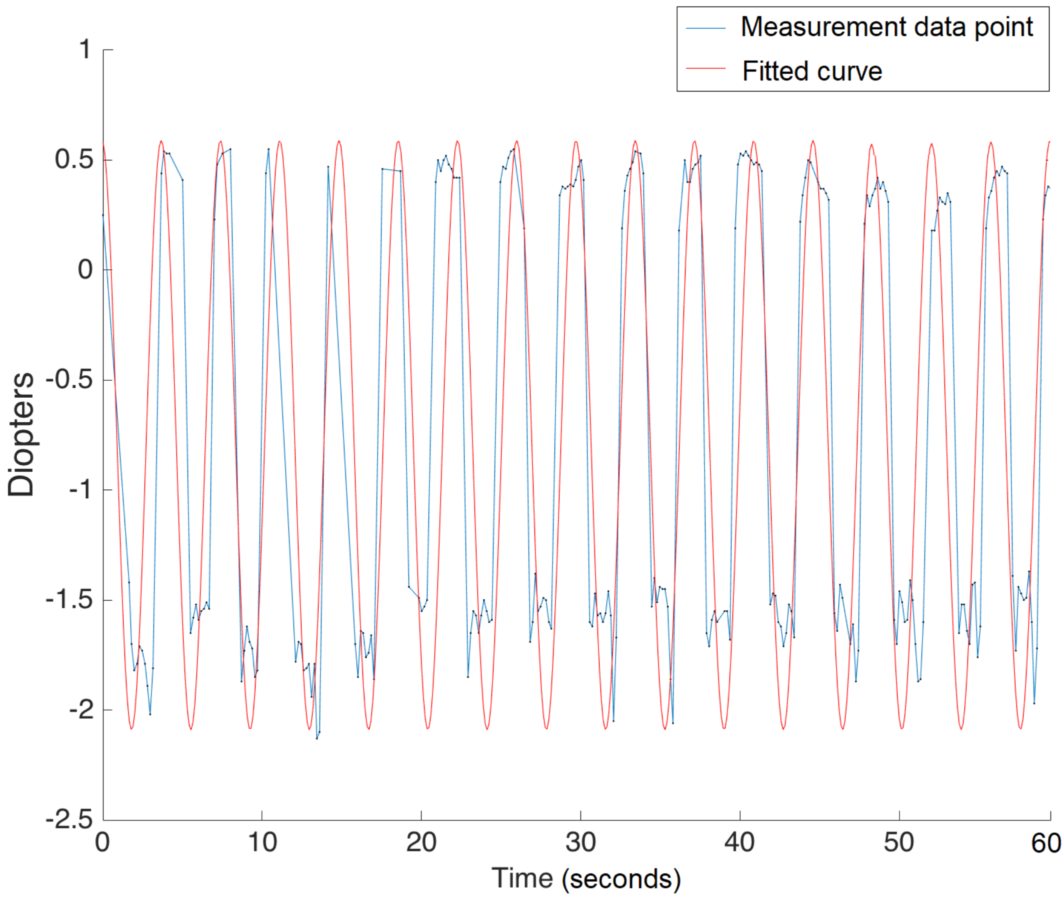

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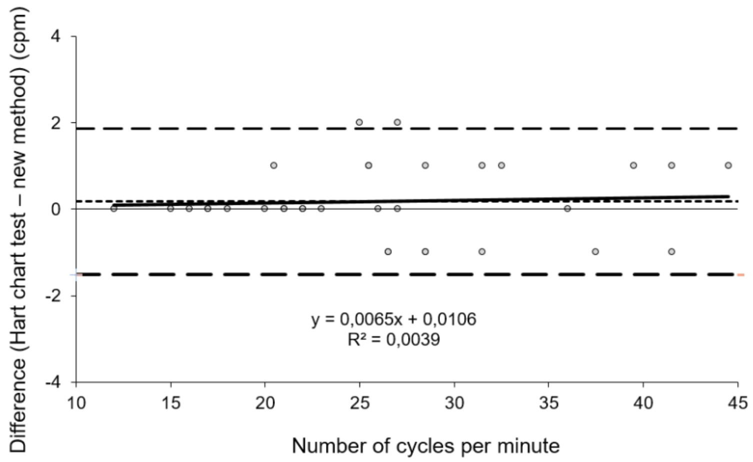

Table 1. Descriptive (mean ± standard deviation) and reliability values for the parameters obtained with the binocular accommodative facility test and the Hart chart test in both experimental sessions.

	Session 1	**Session 2**	**p-value (ES)**	**Pearson r (95%CI)**	**ICC (95%CI)**	**CV (95%CI)**
Number of cycles (new method; cpm)	26.81 ± 6.69	26.69 ± 8.31	0.779 (0.02)	0.97 (0.92-0.99)	0.96 (0.91-0.98)	5.65 (4.32-8.15)
Number of cycles (Hart chart test; cpm)	26.59 ± 6.45	26.28 ± 8.27	0.479 (0.04)	0.98 (0.94-0.99)	0.97 (0.92-0.98)	5.29 (4.05-7.64)
Under-accommodated (%)	39.1 ± 37.7	43.1 ± 35.4	0.025 (0.11)	0.97 (0.92-0.99)	0.96 (0.92-0.98)	17.22 (13.18-24.87)
Under-relaxed (%)	22.2 ± 30.0	24.2 ± 34.2	0.280 (0.06)	0.96 (0.90-0.98)	0.95 (0.85-0.98)	31.21 (23.88-45.07)
Magnitude (D)	1.29 ± 0.22	1.27 ± 0.24	0.081 (0.07)	0.98 (0.94-0.99)	0.97 (0.94-0.99)	2.91 (2.22-4.20)

Note. P-Values and ES (Cohen´s d) are referred to related samples T-tests between both experimental sessions. These values are calculated from 32 out of 33 participants, since data from one participant were discarded for reliability analyses.

Abbreviations: ES = effect size; CI = confidence intervals; ICC = intraclass correlation coefficient; CV = coefficient of variation; cpm = cycles per minute; D = diopters.