Received: 16 November 2022 | Accepted: 21 March 2023

DOI: 10.1111/opo.13136

OPO THE COLLEGE OF OPTOMETRISTS

ORIGINAL ARTICLE

Effect of manipulating the vergence/accommodation and image size mismatches of the ±2D flipper test on the frequency and precision of accommodative facility

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Abstract

Purpose: The ±2.00 D accommodative facility test presents several limitations, including the lack of objective information and inherent characteristics such as vergence/accommodative conflict, change in apparent size of the image, subjective criteria for judging blur and motor reaction time. By using free-space viewing conditions and an open-field autorefractor to monitor the refractive state, we examined the impact of manipulating these factors on the qualitative and quantitative assessment of accommodative facility.

Methods: Twenty-five healthy young adults (24.5 ± 4.5 years) took part in this study. Participants performed three accommodative facility tests (adapted flipper, 4D free-space viewing and 2.5D free-space viewing) under both monocular and binocular conditions in random order. A binocular open-field autorefractor was used to assess the accommodative response continuously, and these data were used to characterise accommodative facility quantitatively and qualitatively.

Results: There were statistically significant differences between the three testing methods both quantitatively ($p < 0.001$) and qualitatively ($p = 0.02$). For the same accommodative demand, a lower number of cycles was obtained for the adapted flipper condition in comparison with the 4D free-space viewing test (corrected p-value < 0.001, Cohen's d = 0.78). However, this comparison did not reach statistical significance for qualitative measures of accommodative facility (corrected p-value = 0.82, Cohen's d 0.05).

Conclusions: These data provide evidence that the qualitative assessment of accommodative facility is not influenced by the inherent limitations of the ±2.00 D flipper test. The use of qualitative outcomes by incorporating an open-field autorefractor allows examiners to increase the validity of the accommodative facility test in both clinical and research settings.

KEYWORDS
autorefractor, ocular accommodation, optometry, visual function

INTRODUCTION

Accommodative facility is defined as the ability to rapidly, accurately and repeatedly change accommodation between two stimulus levels.[1] In an optometric examination, the most frequently used test for the assessment of accommodative facility is the ±2.00 D flipper test, which provides stimulus levels of 0.50 D and 4.50 D when performed with a fixation target at 40 cm. Accommodative facility provides valuable information for the diagnosis of accommodative and binocular disorders,[2] and is more likely to be impaired in individuals with visual symptomatology.[3] Moreover, it differs between myopes and non-myopes.[4,5]

There are a number of factors limiting the ±2.00 D flipper test's generalisability to real-world contexts, namely: (i) when used binocularly, the conflict between the vergence and accommodative demands produced by the lenses; (ii) the change in the apparent size of the retinal image associated with the use of positive and negative lenses; (iii) the subjective criteria for judging whether the target is clear or blurry and (iv) the motor reaction time required to flip the lenses.[6,7] Additionally, as explained by Elliot,[8] this test does not provide objective information (i.e., the change in the accommodative response during the test), and there is no justification for the use of ±2.00 D lenses other than they are the traditional powers. In an attempt to solve these limitations, some researchers have developed an automated accommodative facility test to eliminate operator delays in flipping the lenses[9] or have suggested incorporating an open-field autorefractor to assess the accommodative response objectively during the test.[10,11]

The use of free-space viewing conditions (i.e., using changes in target distance rather than lenses to alter the accommodative stimulus) and comparing accommodative facility measurements under monocular and binocular viewing conditions will allow investigation of the impact of apparent image size, motor reaction time and vergence/accommodative mismatch on the subjective accommodative facility findings. In addition, integration of a binocular open-field autorefractor and evaluation of the accuracy of the accommodative response at both stimulus levels will enable the qualitative assessment of accommodative facility, thus clarifying the impact of the participants' criteria for determining whether the image is clear or blurry. This measure, named 2Q-AF (qualitative and quantitative assessment of accommodative facility) score, has been proposed in a recently published article,[11] and it evaluates the accuracy of the accommodative response to determine whether the accommodative change was appropriate (see the Accommodative facility analysis subsection for more details). To our knowledge, the impact of these factors has not been tested to date. Therefore, the primary objective of this study was to evaluate the impact of vergence/accommodation and apparent image size mismatches, motor reaction time and subjective criteria of a blurred/clear image on qualitative (2Q-AF score) and quantitative (cycles per minute) measures of accommodative facility. To achieve this, accommodative demand was manipulated by modifying the target distance, while the vergence/accommodation mismatch and image size were altered by changing viewing conditions (binocular vs. monocular) and the use of lenses, respectively. We hypothesised that: (i) accommodative facility performance will be lower with greater accommodative demand, (ii) the difference between methods will be reduced when the vergence/accommodation mismatch is absent (i.e., monocular vs. binocular testing) and (iii) the qualitative assessment of accommodative facility with both testing methods will eliminate the variation caused by participants' judgement of a blurred/clear image.

Key points

- Factors such as the vergence/accommodative conflict, apparent size of the image and subjective criteria for judging target clarity limit the generalisability of the ±2.00D flipper test to real-world contexts.
- Incorporation of an open-field autorefractor in free-space viewing conditions permits the quantitative and qualitative assessment of accommodative facility in a more naturalistic manner.
- Qualitative measurements of accommodative facility are less influenced by the factors that affect the ±2.00D flipper test.

METHODS

Participants

A total of 25 healthy young adults (mean age ± standard deviation = 24.5 ± 4.5 years; range: 19–30 years) took part in this study. The inclusion criteria were: (i) absence of ocular or systemic disease; (ii) corrected monocular visual acuity ≤0.0 log MAR in each eye; (iii) between 18 and 35 years of age; (iv) no history of refractive surgery or orthokeratology; (v) refractive error between −5.00 D and +3.00 D and ≤0.75 D of astigmatism in each eye; (vi) no significant uncorrected refractive error that could affect either accommodation or vergence, that is myopia <0.50 D, astigmatism and anisometropia <0.50 D and/or hyperopia <1.50 D; (vii) scoring ≤24 on the Conlon Survey[12] and <21 on the Convergence Insufficiency Symptom Survey,[13] which assess symptoms of visual discomfort and convergence insufficiency, respectively; (viii) presenting normative values for amplitude of accommodation and accommodative response and (ix) having normal values for near point of convergence, heterophoria and vergence as indicated by Scheiman and Wick.[14] The present study followed the tenets of the Declaration of Helsinki and was approved by the University of Granada Institutional Review Board (approval number: 1786/CEIH/2020). All participants read and signed an informed consent before their enrollment in this investigation.

Procedure

Two experimental sessions were conducted on different days. Both were scheduled at the same time of the day (±1 h) to avoid the influence of circadian variations. In the first session, participants completed the visual symptomatology questionnaires (the Conlon Survey[12] and the Convergence Insufficiency Symptom Survey[13]), and an investigator performed slit lamp and direct ophthalmoscopy examinations as well as a subjective refraction using an endpoint criterion of maximum plus consistent with best visual acuity. Then, the amplitude of accommodation (push-up technique), accommodative response (monocular estimated method retinoscopy), near and distance heterophoria (cover test), near point of convergence and near and distance vergence ranges (step vergence method using a prism bar) were assessed to determine eligibility. Fusion/suppression was assessed using a standard Worth-4-dot test at near (40 cm) and far (5 m) distances, and eye dominance was determined by the hole-in-the-card method.[15] A preliminary check that participants were able to perform the ±2.00 D flipper test under monocular and binocular (using a vectographic slide to monitor for suppression) conditions was conducted. If participants met all of the inclusion criteria, spherical disposable Hydroxyethyl methacrylate (HEMA) and Ocufilcon D (55% water content) soft contact lenses (SCLs) were ordered (Servilens Fit & Covers Company, lens55.com) based on the refractive and keratometric assessment with vertex distance adjusted for. The spherical equivalent was used for astigmatism less than 0.75 D. SCLs were ordered with the exact refraction or spherical equivalent (as necessary), and with an over-refraction of +2.00 D (see 'Accommodative facility assessment' subsection for more details) for each participant. In a second session, an SCL fitting evaluation and an over-refraction were performed to check for appropriate centration, movement and visual acuity. Then, the six accommodative facility conditions (3 testing methods [2.5D free-space viewing test, 4D free-space viewing test and adapted flipper test] × 2 viewing conditions [binocular and monocular dominant eye]) as described below were conducted in random order to control for possible learning or fatigue effects. A 5-min break was allowed between tests, and participants were familiarised with the tests prior to data collection to ensure that they understood the procedures.

Accommodative facility evaluation

Three different accommodative facility procedures were performed to achieve the objectives of this study (see Figure 1 for a schematic illustration). For all tests, the targets used had a resolution of 0.20 logMAR and luminance of approximately 45 cd/m^2. For all tests, participants were asked to change their focus as quickly as possible between the two accommodative levels (to keep the targets clear) over a 60 second period, while the refractive state of the dominant eye was measured continuously with a WAM-5500 binocular open-field autorefractor (WAM-5500, grandseiko.com).

(i) The 2.5D free-space viewing test: This test was described by Vera et al.[10] Briefly, participants had to focus alternatively between a distant (5 m) and near (40 cm) high-contrast (90%) Hart Chart. A custom-made target was used for the near chart, which allowed participants to look at the far target without interfering with the participant's gaze and minimising the vertical movement of the eyes

(ii) The 4D free-space viewing test: This was identical to the 2.5 D free-space viewing test described above, except the far and near targets were placed at 2 m and 22 cm, respectively, to match the accommodative demands of the ±2.00 D lens flipper test (i.e., 0.50 and 4.50 DS).

(iii) The adapted flipper test: For this test, participants wore SCLs with an over-correction of +2.00 D, and used a −4.00/plano flipper. Due to the characteristics of the experimental set-up, flipping the lenses was physically impossible because participants were positioned on a chin and forehead rest. Therefore, the flipper was moved vertically (rather than flipped) by the participant. A near target was placed at 40 cm using the ruler attached to the upper part of the autorefractor. When participants viewed through the plano and −4.00 lenses, the total accommodative demand (SCL + flipper + target viewing distance) was 0.50 D and 4.50 D, respectively. This accommodative demand is the same as for the standard clinical ±2.00 D lens flipper test and the '4D free-space viewing test'.

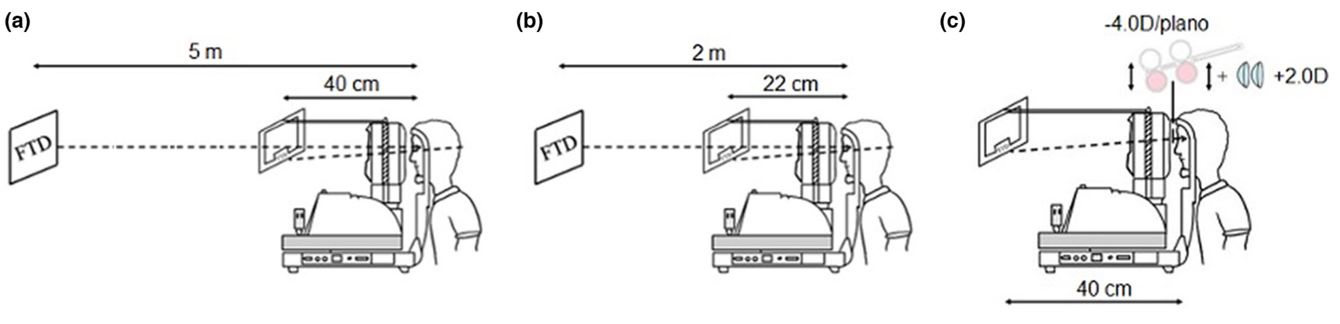

FIGURE 1 Graphical illustration of the three accommodative facility tests performed in this study: (a) the 2.5D free-space viewing test, (b) the 4D free-space viewing test and (c) the adapted flipper test.

These conditions, including monocular and binocular assessments for each protocol, allowed the impact of apparent image size, motor reaction time and vergence/accommodative mismatch on the subjective accommodative facility rate to be determined.

Accommodative facility analysis

For data analysis, we used the participant's refractive state obtained with the open-field autorefractor during the 60-second accommodative facility tests, and following the methodology described in detail elsewhere.[10] The accommodative response (mean and standard deviation) was recorded at each accommodative level (5 m [0.2D], 2 m [0.5D], 0.4 m [2.5D] and 0.22 m [4.5D]) for 60 s. These baseline values were considered as reference metrics to assess accommodative response accuracy at each stimulus level (e.g., the corrected refractive state of a participant at far could be 0.09 D, and this was the value considered for further analysis). Briefly, quantitative and qualitative outcomes were obtained from the accommodation measurement signal after estimating an approximate frequency by counting the signal's zero-crossings. This approximate frequency was used to fit a sinusoid at that frequency to the input signal with amplitude, phase and DC offset as free parameters using the Levenberg–Marquardt damped least-squares method (see Ref. [10] for a more detailed explanation of this process). This method is implemented using a solver from the Matlab Optimization Toolbox. This process obtains the number of cycles, percentage of inaccurate cycles of accommodation and dis-accommodation (i.e., inaccurate cycles divided by the total number of cycles), and the mean magnitude of accommodative change between the two accommodative levels. An inaccurate cycle was defined as an accommodative response varying by more than one standard deviation, either over- or under-accommodation, from the mean refractive state at each accommodative level. As an example, for the 4D free-space viewing test, accommodative data taken for targets at 2 m and 22 cm were used to assess the accuracy of the response at far and near, respectively. As previously stated, a new equation (2Q-AF score), considering the number of cycles per minute (cpm) – quantitative data, and the percentage of cycles under-accommodated and under-relaxed (qualitative data) (Equation 1), has been proposed for the assessment of accommodative facility.[11] Here, we considered both the total number of cycles and 2Q-AF score for statistical analyses. Figure 2 shows an example of the procedure for accommodative facility analysis.

$$(2Q-\text{AF score}) = \text{cpm} - \text{cpm} \times \left(\frac{\%\,\text{of near errors} + \%\,\text{of far errors}}{2} \right) \tag{1}$$

Statistical analyses

Data normality and equality of variance were determined by the Shapiro–Wilk and Levene tests, respectively. These analyses did not reach statistical significance ($p > 0.05$ in all cases), and accordingly, parametric statistics were applied for data analyses. Two separate repeated measures analyses of variance, with viewing conditions (binocular and monocular) and testing method (adapted flipper, 4D free-space viewing and 2.5D free-space viewing) as within-participants factors, were carried out for the total number of cycles (quantitative measure) and the 2Q-AF score (qualitative measure). In addition, exploratory correlation analyses (Pearson's r) were performed between the different experimental conditions for the two dependent variables (cycles per minute and 2Q-AF score). The level of statistical significance was established at 0.05, and the Holm–Bonferroni procedure was applied for multiple comparisons. Standardised effect sizes were reported by means of the partial η^2 (η^2_p) for Fs and the Cohen's d (d) for t-tests. All statistical tests were performed with the JASP statistical package (version 0.16.3; The JASP team, jasp-stats.org/).

RESULTS

Table 1 shows descriptive and statistical values for the qualitative and quantitative results obtained for the three accommodative facility tests under both monocular and binocular conditions.

Analysis of the number of cycles (quantitative assessment) revealed statistically significant differences for 'testing method' ($F_{2,48} = 21.44$, $p < 0.001$, $\eta^2 = 0.27$), whereas the main factor of 'viewing conditions' and the interaction between the testing method and viewing conditions did not reach statistical significance ($F_{1,24} = 2.07$, $p = 0.16$; and $F_{2,48} = 1.01$, $p = 0.37$, respectively). Pairwise comparisons between the three testing methods (without differentiating between monocular and binocular conditions) showed a significantly lower number of cycles for the adapted flipper test compared with the 4D free-space and 2.5D free-space viewing tests (corrected p-value <0.001 in both cases, and Cohen's d = 0.78 and 1.30, respectively). Similarly, the number of cycles completed was significantly lower for the 4D free-space viewing test compared with the 2.5D free-space viewing test (corrected p-value = 0.01, Cohen's d = 0.52) (Figure 3, panel A).

For the 2Q-AF score, a statistically significant effect was observed for 'testing method' ($F_{2,48} = 4.39$, $p = 0.02$, $\eta^2 = 0.07$) but again, no significant differences were obtained for the main factor of 'viewing conditions' and the interaction between testing method and viewing conditions ($F_{1,24} = 2.33$, $p = 0.14$; and $F_{2,48} = 1.28$, $p = 0.29$, respectively). Pairwise comparisons between the three testing methods (without differentiating between monocular and

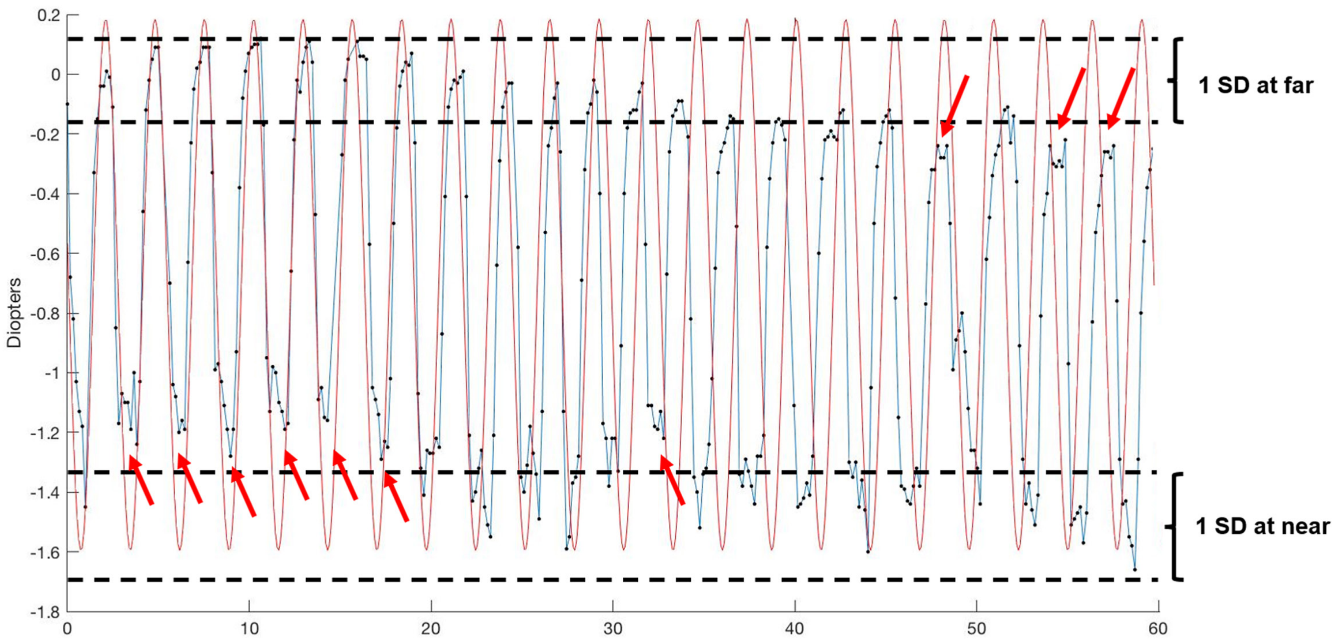

FIGURE 2 Graphical illustration of the accommodative facility analysis from one subject in the 2.5D free-space viewing test condition. The red arrows indicate the inaccurate responses at each accommodative level.

TABLE 1 Descriptive values (mean ± standard deviation) and pairwise comparisons (Holm–Bonferroni corrected *p*-value) of the accommodative facility measurements taken in this study.

		Adapted flippers	4D free-space viewing	2.5D free-space viewing	P1	P2	P3
Total cycles (cpm)	Binocular	9.6 ± 8.4	18.0 ± 11.2	25.0 ± 11.9	**0.007**	**<0.001**	**0.01**
	Dominant eye	14.0 ± 7.7	21.4 ± 12.0	24.9 ± 10.2	**0.01**	**<0.001**	0.18
2Q-AF score	Binocular	9.2 ± 8.0	10.2 ± 7.4	15.0 ± 8.3	0.63	**0.02**	0.06
	Dominant eye	13.7 ± 7.7	12.0 ± 7.2	15.3 ± 7.3	0.75	0.75	0.26

Note: P1 = adapted flippers versus 4D free-space viewing; P2 = adapted flippers versus 2.5D free-space viewing; P3 = 4D free-space viewing versus 2.5D free-space viewing. Corrected *p*-values <0.05 are in bold. cpm = cycles per minute. 2Q-AF, qualitative and quantitative assessment of accommodative facility.

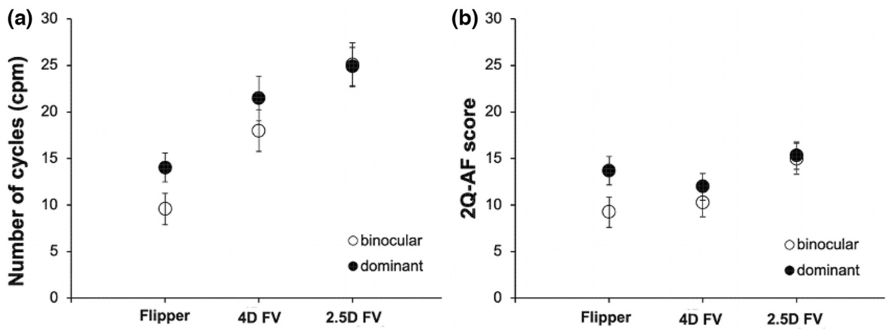

FIGURE 3 Influence of the accommodative facility test on quantitative (a) and quantitative (b) outcomes under monocular (filled circles) and binocular (empty circles) conditions. Error bars indicate one standard error. 2Q-AF, qualitative and quantitative assessment of accommodative facility; 2.5D FV,2.5D free-space viewing test; 4D FV, 4D free-space viewing test;cpm, cycles per minute.

binocular conditions) revealed a higher 2Q-AF score for the 2.5D free-space viewing test than the adapted flipper and 4D free-space viewing tests (corrected *p*-value = 0.04, Cohen's d = 0.49; and corrected *p*-value = 0.03, Cohen's d = 0.54, respectively). However, the comparison between the adapted flipper and 4D free-space viewing tests did not reach statistical significance (corrected *p*-value = 0.82, Cohen's d = 0.05) (Figure 3, panel B).

Correlation analyses between the different methods showed significant correlations between the 2.5D free-space viewing and 4D free-space viewing tests. Pearson's correlation coefficients for the quantitative and qualitative measures were 0.50 ($p=0.01$) and 0.80 ($p<0.001$), respectively.

DISCUSSION

These data provide new insight into the influence of the vergence/accommodation and apparent image size mismatches, motor reaction time and subjective judgement of clarity on accommodative facility rates. As expected, accommodative facility rates were modulated as a function of the accommodative demand, observing lower (worse) values of qualitative and quantitative accommodative facility when testing at higher dioptric stimuli.[16] When accommodative facility is performed under monocular conditions (avoiding the vergence-accommodation mismatch), the differences between the three testing methods were lower than under binocular conditions (see Table 1). When testing at the same dioptric demand (4D free-space viewing and adapted flipper tests), the number of cycles performed accurately based on the 2Q-AF score was significantly lower than when simply counting the number of cycles (quantitative assessment). Similarly, the free-space viewing conditions provide a better quantitative performance (higher number of cycles) compared with the adapted flipper test; however, these differences disappear when considering qualitative results (2Q-AF scores). These findings bring into question whether accommodative facility values assessed with the ±2.00 D flipper test can be extrapolated to a real-world context where changes in accommodation occur in free-space viewing conditions.

In agreement with our initial hypothesis, both quantitative and qualitative accommodative facility was lower at higher accommodative demands.[16] It is noteworthy that these differences were present for both quantitative (cycles per minute) and qualitative (2Q-AF score) measurements under binocular conditions. However, the influence of the dioptric demand on accommodative facility was reduced under monocular conditions. This might be due to eliminating the vergence/accommodation mismatch during monocular testing. The difference between the vergence and accommodative demands during binocular viewing will be greater at higher accommodative stimulus levels. Therefore, it seems that accommodative facility performance, particularly under binocular conditions, is dependent upon the magnitude of accommodative change (i.e., the difference between the two accommodative levels). Therefore, eye care practitioners should interpret the results based on the method of testing (free-space viewing vs. flippers) and the change in accommodative demand (2.5D vs. 4.0D). These parameters should be recorded routinely alongside the results in cycles per minute.

An inter-methods comparison allowed an assessment of the influence of apparent image size and motor reaction time on accommodative facility since these factors were absent in the free-space viewing test. It is interesting to note that the comparison between the adapted flipper and free-space tests at the same accommodative demand (4D free-space viewing test) reached statistical significance ($p=0.01$, $d=0.55$) for the number of cycles per minute (quantitative measure), but not for the 2Q-AF score qualitative measure ($p=0.75$, $d=0.17$). This mismatch of vergence and accommodative demands caused by the use of a fixed distance (40 cm) in the ±2.00 D lens flipper test rarely occurs in real-world scenarios, and thus, it could be considered as a limitation of the validity of this clinical measure. To explore this effect, we compared the qualitative and quantitative results obtained with the adapted flipper and free-space viewing tests (4D free-space viewing test) under binocular conditions. Here, the vergence/accommodation conflict seemed to modulate the quantitative (cycles per minute: $p=0.007$, $d=0.60$) but not the qualitative (2Q-AF score: $p=0.63$, $d=0.08$) findings. This suggests that the combined effects of apparent image size and motor reaction time, as well as the vergence/accommodation conflict associated with the use of flippers are significant for the accommodative facility rate, but the effects are negligible when the accuracy of the accommodative response is considered.

Although beyond the objectives of the present study, the 2Q-AF score seems to be a more robust measure of accommodative facility than the number of cycles per minute, since the correlations between the three methods tested here were substantially higher for the qualitative measure (2A-AF score). For example, Pearson correlation coefficients between the 2.5D free-space and 4D free-space viewing tests were 0.50 and 0.80 for the number of cycles and 2Q-AF score, respectively. Interestingly, the need to judge subjectively when the target is clear or blurred can be controlled with the qualitative assessment. Due to the observed differences between the qualitative and quantitative results, assessment of the accuracy of the accommodative changes could be of value in the clinical setting, providing a more valid measurement of accommodative facility. In addition, adoption of objective measures could be of particular value in populations who find it difficult to understand or execute this procedure (e.g., persons with special needs).[17]

Taken together, these results highlight that quantitative and qualitative measures of accommodative facility cannot be considered as interchangeable and must be analysed and interpreted separately. In this regard, previous studies have suggested that accommodative facility rates may be considered as partial predictors of visual discomfort and myopia progression[3,5,18] and a diagnostic sign for accommodative and binocular disorders.[2] In future studies, it would be valuable to explore the link between qualitative measures of accommodative facility and visual discomfort in patients with accommodative and binocular disorders.

The implementation of qualitative measures may provide some advantages in clinical practice by the objective assessment of accommodative facility. Nevertheless, as specified by Otero and colleagues,[9] it is important that accommodative facility tests are conducted under predictable conditions (i.e., two fixed focal planes), which is not what usually occurs in real-world contexts. Moreover, further research is required to develop accommodative facility tests that are similar to everyday circumstances.

These data provide new information regarding the impact of changes in apparent image size, motor reaction time and vergence/accommodation conflict on the frequency and precision of accommodative facility. However, there are several aspects that require further investigation. First, there is evidence of inter-individual variability in the dynamics of ocular accommodation,[19] and the results should be interpreted cautiously in this regard. Second, we did not explore the impact of age, refractive error or the presence of accommodative or binocular anomalies on the quantitative and qualitative measurements of accommodative facility, and this requires further investigation. Third, we checked that participants were able to perform the ±2.00 D flipper test using a vectographic slide to monitor for suppression. However, we did not monitor for suppression during the assessment of accommodative facility in the three binocular testing methods. Lastly, there are several aspects that may be seen as a limitation to the incorporation of this qualitative method into clinical practice. The ±2.00 D lens flipper test has been traditionally used in clinical optometric practice, and reference data have been established for different populations and visual conditions. In addition, the proposed qualitative method requires the use of a specific instrument (i.e., an open-field autorefractor) and additional analysis of the recorded data. A reduction in the cost of this technology and automation of the analysis by the development of user-friendly software will help to ease these disadvantages.

CONCLUSIONS

These results show that the qualitative assessment (2Q-AF score) of accommodative facility in free space is less influenced by the vergence/accommodation and apparent image size mismatch, motor reaction time and subjective criteria to determine whether the image is blurred or clear, compared with conventional clinical testing. Based on these results, the use of free-space testing allows the measurement of accommodative facility in a more naturalistic manner. Inclusion of qualitative outcomes would be helpful to increase the validity of this parameter in clinical practice and may help gain a better understanding of the association between accommodative facility and visual discomfort, as well as accommodative and binocular disorders.

AUTHOR CONTRIBUTIONS

Jesus Vera: Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal); supervision (equal); writing – original draft (equal); writing – review and editing (lead). **Beatriz Redondo Cabrera:** Conceptualization (equal); data curation (equal); methodology (equal); supervision (equal); writing – original draft (equal); writing – review and editing (supporting). **Jose Miguel Martínez Tovar:** Investigation (equal); methodology (equal); writing – original draft (supporting). **Rubén Molina Romero:** Data curation (equal); methodology (equal); writing – original draft (supporting). **George Alex Koulieris:** Conceptualization (equal); data curation (equal); formal analysis (equal); software (lead); validation (lead); visualization (lead); writing – original draft (supporting). **Peter Allen:** Conceptualization (equal); validation (equal); writing – original draft (supporting); writing – review and editing (equal). **Raimundo Jimenez:** Conceptualization (equal); investigation (equal); methodology (equal); supervision (equal); writing – original draft (equal); writing – review and editing (supporting).

ACKNOWLEDGEMENTS

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.

CONFLICTS OF INTEREST

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

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How to cite this article: Vera J, Redondo B, Martínez-Tovar JM, Molina R, Koulieris GA, Allen PM, et al. Effect of manipulating the vergence/accommodation and image size mismatches of the ±2D flipper test on the frequency and precision of accommodative facility. *Ophthalmic Physiol Opt*. 2023;00:1–8. https://doi.org/10.1111/opo.13136