Computers in Biology and Medicine 186 (2025) 109718

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/compbiomed

Wavefront sensing: A breakthrough for objective evaluation of dynamic accommodation in accommodative dysfunctions

Jessica Gomes, Sandra Franco *

Centre of Physics of the Universities of Minho and Porto, University of Minho, 4710-057, Braga, Portugal

ARTICLE INFO

Keywords:
Wavefront sensing
Aberrometry
Hartmann-shack
Accommodation
Accommodative dysfunctions

ABSTRACT

The purpose of this study was to use wavefront sensing as an objective method to detect and assess dynamic accommodation in subjects with accommodative dysfunctions and symptoms related to near-vision tasks.

Sixty-three subjects were divided into control (N = 18), symptomatic without any accommodative dysfunction (SWD) (N = 18), infacility of accommodation (INFA) (N = 6), excess of accommodation (EA) (N = 9), and insufficiency of accommodation (INSA) (N = 12) groups. Accommodation was stimulated in different cycles of accommodation and disaccommodation while ocular aberrations were measured. Dynamic accommodation was computed from ocular wavefront aberrations and then analysed, including response time, peak velocity, and microfluctuations.

Subjects with accommodative dysfunctions showed alterations in accommodative responses compared to the control group, characterized by slower and excessive/reduced responses, as well as an increase in accommodative microfluctuations and difficulty in relaxing accommodation to different accommodative demands. The SWD group showed significant changes compared to the control group, suggesting accommodative problems not previously detected in clinical examinations and explaining the symptoms reported by these subjects. The specific patterns of the characteristics of dynamic accommodation are presented for the different accommodative dysfunctions.

The objective assessment of dynamic accommodation using wavefront sensing, analysed for different accommodative demands, provides a comprehensive approach to the detection and characterisation of accommodative dysfunctions. This method enables the improvement of the precision of the diagnosis of accommodative dysfunctions and allows its detection in cases that may not be detected by current clinical examinations. In addition, this method may contribute to personalized treatment planning, potentially improving patient outcomes in clinical practice.

1. Introduction

Accommodation is a fundamental mechanism of the visual system that allows clear images on the retina of objects at different distances. Static accommodation refers to the accommodative response to an object at a specific distance and time, while dynamic accommodation involves an adjustment of the visual system to focus objects at varying distances and their fluctuations over time for a certain stimulus. This procedure is characterized by depending on the oculomotor system and neurological control signals triggered by a blurred retinal image [1,2]. Previous authors reported variations between dynamically and statically recorded accommodative responses [3].

The evaluation of dynamic accommodation may provide extensive information, including latency, response time, velocity, acceleration, and microfluctuations of accommodation and disaccommodation [1, 4–8]. Since the visual system is constantly exposed to variations in the viewing conditions and undergoes microfluctuations even with sustained focus [8], the assessment of dynamic accommodation is closer to real daily conditions and may provide valuable insights beyond only assessing static accommodation, such as amplitude and lag of accommodation, obtained by the current clinical examinations. The parameters obtained from dynamic accommodation contribute to a better understanding of the accommodative process and may be particularly useful in subjects with accommodative disorders.

Shack-Hartman wavefront sensors provide accurate measurements of the wavefront shape, and several studies have shown it to be a reliable

* Corresponding author.
E-mail addresses: jessicarafamg@gmail.com (J. Gomes), sfranco@fisica.uminho.pt (S. Franco).

https://doi.org/10.1016/j.compbiomed.2025.109718
Received 4 November 2024; Received in revised form 27 December 2024; Accepted 17 January 2025
Available online 22 January 2025
0010-4825/© 2025 Published by Elsevier Ltd.

method of analysing the accommodative response computed from defocus aberration [9–11]. Dynamic measures of ocular accommodation can be obtained by taking measurements across time and for different stimuli [12–14]. A prior study employed this approach to control the accommodative response during subjective refraction, demonstrating its reliability and utility [15].

Accommodative dysfunctions impact a significant number of individuals, resulting in symptoms and posing particular challenges for those engaged in extended near-vision tasks [16,17]. Although accommodative dysfunctions have been clinically reported, their underlying mechanisms remain largely unexplored. Furthermore, there is a lack of studies characterizing in detail the accommodative behaviour of these subjects, i.e., the dynamic features of accommodation. In addition, the subjectivity of the exams and the dissimilarity in the diagnostic criteria used make it difficult to detect and diagnose effectively. An objective dynamic assessment of accommodation may provide deeper information to characterise and understand the accommodative behaviour of subjects with accommodative dysfunctions, improving their diagnosis. The purpose of this study is to use wavefront sensing as a novel objective method to assess and detect accommodative problems and to characterise the dynamic accommodative properties in these subjects.

2. Methods

2.1. Participants

Participants were recruited through an email sent to all undergraduate, masters and doctoral students, as well as researchers and professors from all departments at the University of Minho. To be eligible for the study, individuals had to be healthy and under the age of 35, excluding presbyopes and pre-presbyopes. The email explained the aims of the study and gave a brief description of the procedures, explaining that they consisted of a habitual eye exam with an additional exam to assess the optical quality of the eye, all of which non-invasive. Those interested in participating provided their email address so that data collection could be scheduled. Participants were encouraged to schedule in the morning to avoid the effects of stress from their work/study day and before performing long visual tasks. None of the participants had any prior contact with the system used to measure ocular aberrations.

The participants first underwent an eye examination, including objective (static retinoscopy with contralateral fogging technique to control accommodation) and subjective refraction. The subjective refraction started from the value of the objective refraction, and the maximum plus lens for best visual acuity was found for each eye. The assessment of refractive error was performed without the use of cycloplegia. Previous studies suggested that the most significant differences between cycloplegic and non-cycloplegic refraction were observed in children and for high hyperopia [18,19]. A previous study also suggested that non-cycloplegic refraction using a contralateral fogging technique is effective as cycloplegic refraction for measuring refractive error and has no clinical impact [20].

Binocular vision and accommodation were also assessed. The amplitude of accommodation was measured by the Sheard method, the lag of accommodation by the MEM (monocular estimated method) retinoscopy, and the facility of accommodation at near vision with lenses ±2.00D. The subjects' accommodative and binocular dysfunctions were classified according to the criteria of Lara et al. [21], as shown in Table 1, and they never received any treatment for this condition. Best-corrected visual acuity was 20/20 or better, and subjects with binocular vision dysfunctions, history of ocular pathology, ocular surgery, orthokeratology, or use of medications that could affect the visual system were excluded. To determine whether they were symptomatic or asymptomatic, the CISS survey was administered to the subjects, and they were considered symptomatic with a score higher than or equal to 21 [22].

After this examination, sixty-three participants were included in the study and were divided into four groups: a control group of asymptomatic subjects without any accommodative dysfunction (control); a group of symptomatic subjects but without any accommodative dysfunction (SWD); a group with infacility of accommodation (INFA); a group with an excess of accommodation (EA); and a group with insufficiency of accommodation (INSA).

Table 1
Diagnostic criteria of accommodative and binocular dysfunctions.

	Accommodative Dysfunctions		
	Infacility of accommodation	Excess of accommodation	Insufficiency of acommodation
Signals	• Monocular accommodative facility ≤6 cpm and binocular ≤3 cpm • PRA ≤1.25 D and NRA ≤1.50 D	• Variable VA • Variable static retinoscopy/ subjective refraction • Monocular accommodative facility ≤6 cpm with difficulty with the lens +2.00 D And two of these: • Binocular accommodative facility ≤3 cpm with difficulty with the lens +2.00 D • MEM < +0.25 D • NRA ≤1.50 D	• AA at least 2.00 D below 15−0.25 × *age*15−0.25 × age • Monocular accommodative facility ≤6 cpm with difficulty with the lens −2.00 D And two of these: • Binocular accommodative facility ≤3 cpm with difficulty with the lens −2.00 D • MEM > +0.75 D • PRA ≤1.25 D
	Binocular dysfunctions		
	Convergence insufficiency	Convergence excess	Basic exophoria
Signals	• Exophoria at near >6Δ • PFV at near ≤11/14/3 (blur/break/ recovery) • NPC >10 cm And two of these: • AC/A ratio <3/1 • Fails BAF with +2.00 D (≤3 cpm) • MEM < +0.25 D • PRA ≤1.50 D	• Esophoria >2Δ • NFV ≤8/16/7 (blur/break/ recovery) And two of these: • AC/A > 7/1 • Fails BAF with −2.00 D (≤3 cpm) • MEM > +0.75 D • PRA ≤1.25 D	• Exophoria of approximately of equal magnitude at near and distance (within 5 D) • PFV <11/14/3 and <4/8/5 (blur/break/recovery) at near and distance, respectively And two of these: • Normal AC/A ratio • BAF <3 cpm • MEM <0.25 D • NRA <1.50 D

cpm: cycles/minute; PRA: positive relative accommodation; NRA: negative relative accommodation; VA: visual acuity; MEM: monocular estimated method; AA: amplitude of accommodation; PFV: positive fusional vergence; NFV: negative fusional vergence; NPC: near point of convergence; BAF: binocular accommodative facility.

The study adhered to the tenets of the Declaration of Helsinki and was approved by the Ethical Subcommission of Life and Health Science of the University of Minho (SECVS 029/2014 (ADENDA), July 2, 2019). All subjects signed an informed consent with an explanation of the procedures. This explanation consisted of a brief description of the technical procedures of the exams.

2.2. Set-up and procedure

An adaptive optical system with an in-house Hartmann-Shack aberrometer (Thorlabs WF150-7AR) was used to assess in real-time ocular aberrations in the subject's right eye while inducing accommodation with negative lenses in the same eye. The contralateral eye was occluded using an eye patch to ensure monocular viewing conditions. The powers of the lenses used were −1.00 D, −2.50 D, and −5.00 D. The aberrometer had a resolution of 1280 × 1024 and 39 × 31, with lenses working at a frequency of 10 Hz. The power of the super luminescent diode (SLD), used to generate the optical beam, was 10 μW (L8414-04,

Hamamatsu, Shizuoka, Japan) at the eye and had a spectral maximum at 830 nm. The beam diameter within the wavefront sensor was approximately 4 mm, with an effective diameter of 2 mm used for aberrations measurement. A schematic representation of the system is shown in Fig. 1.

The subject's eye was aligned with the system and stabilised using a chin and forehead support unit. The target consisted of a white cross on a black background correspondent to a visual acuity of 20/25 and simulated to be at far (≈6 m). The subjects were instructed to keep it in focus as best they could. The subject's refractive error, including sphere and astigmatism, was fully corrected with lenses during the measurements. This correction was on the basis of the subjective refraction previously determined.

Each subject was exposed to different cycles of accommodation and disaccommodation. Disaccommodation is the relaxation of the ocular accommodative system after a stimulus (when changing from near to far), involving the relaxation of the ciliary muscle and decrease of the lens power [6,23]. Considering the distance of 20 mm from the lens to the eye and the conditions of the simulated far target, the accommodation was stimulated in the following order: 0.00 D → 1.00 D → 0.00 D → 2.45 D → 0.00 D → 4.73 D → 0.00 D. Each lens was placed in front of the subject's eye for approximately 5 s, resulting in approximately 50 measures for each accommodative stimulus.

2.3. Data analysis

Accommodation response was calculated by the Zernike second-order spherical defocus term and taking into account the lens in front of the subject's eye used to stimulate accommodation by the formula [24]:

$$AR = \frac{Mi - M - Pl \times (1 + d \times M) \times (1 + d \times Mi)}{1 - d \times Pl \times (1 + d \times M)}, \quad (5.6.1)$$

where AR is the accommodation response, Mi is the initial spherical equivalent value of the subject, M is the spherical equivalent at each instant, Pl is the power of the lens used to stimulate accommodation, and d is the distance between the lens and the subject's eye. The spherical equivalent (M) was obtained using the following formula [25]:

$$M = \frac{-4\sqrt{3}\, Z_2^0}{r^2}, \quad (5.6.2)$$

where Z_2^0 represents the defocus term and r represents the pupil radius. Measurements were taken and analysed for a pupil radius of 2.25 mm, ensuring that all subjects had a pupil size greater than or equal to this value.

Initial state refers to the initial accommodative state of the subjects before being submitted to accommodative stimuli and residual accommodation is the accommodation remaining even after it has attempted to shift its focus back to a resting state following an accommodative stimulus.

The means were calculated when accommodation was stabilised, i.e. between the time when the accommodative or disaccommodative response reached 98 % of its total change and the end of the stimulus [26].

The data were visually analysed, and any accommodative responses with random patterns and blinks were excluded from the analysis.

According to a previous study [27], the strategy used to analyse accommodation and disaccommodation responses should be chosen for each subject to obtain the most accurate analysis and the parameters to properly characterise the accommodation and disaccommodation dynamics. Therefore, two different models were fitted to the AR for each subject, and the model that best fitted the original data was selected. This was done by calculating the mean RMS error obtained between the fitted function and the original data.

The exponential model was given by the following function (Fig. 2):

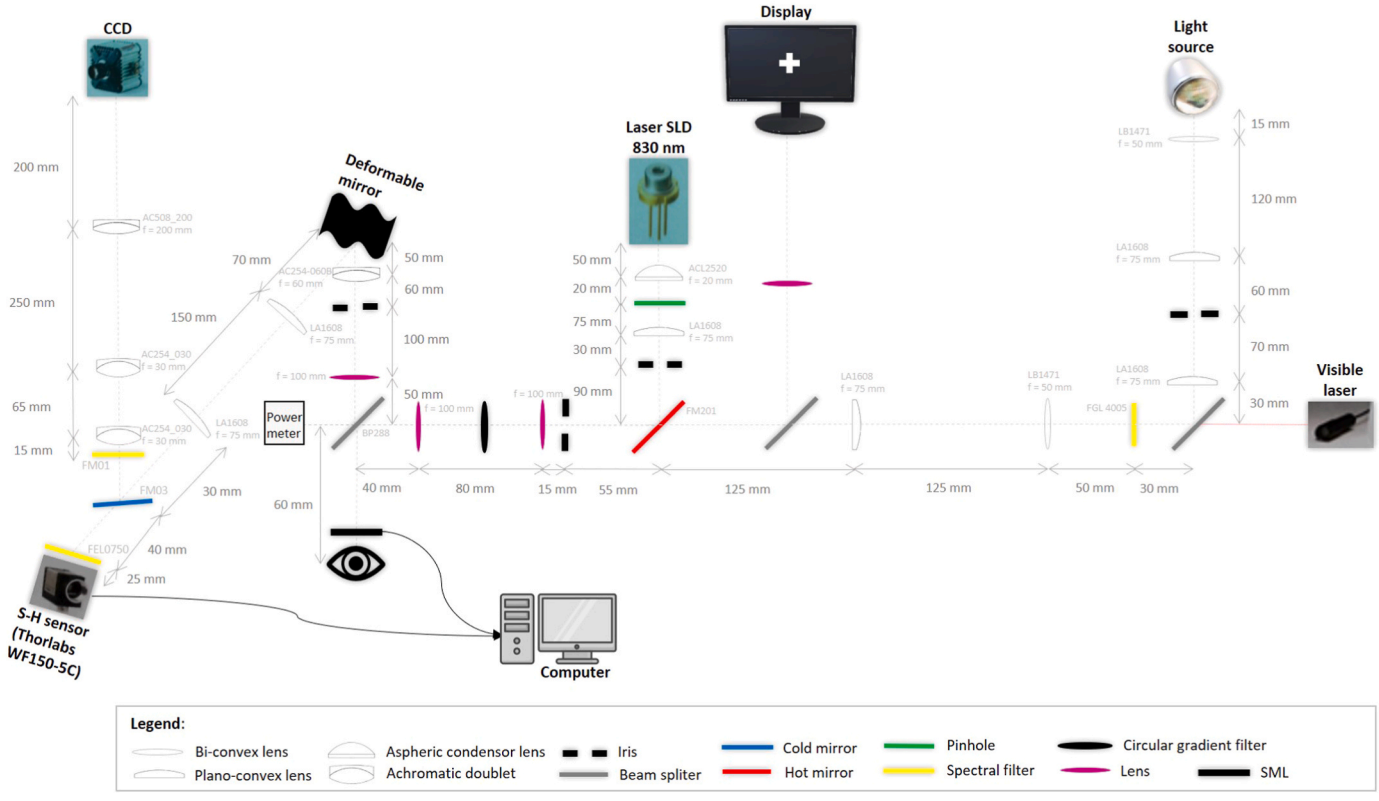

Fig. 1. Schematic representation of the optical system used for measurements.

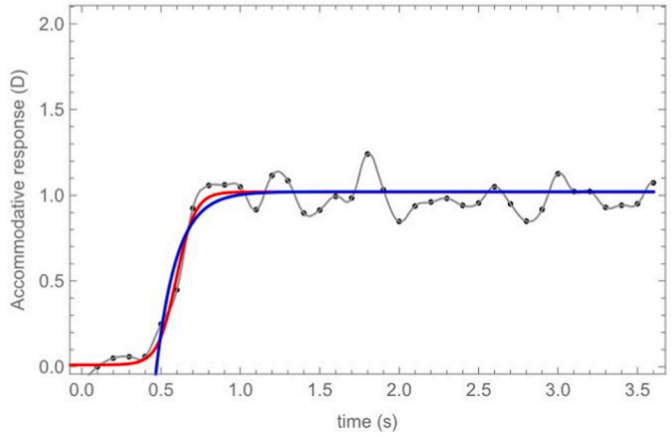

Fig. 2. The Boltzmann sigmoidal function (red) and the exponential function (blue) fitted to the experimental data points (black) of accommodation of one subject for 1.00D of accommodative stimulus. Grey curves show smoothed interpolation of the accommodative responses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$Ac = r_0 \pm a\left(1 - e^{-\frac{x}{\tau}}\right), \tag{5.6.3}$$

where Ac is the AR at each moment in diopters, r_0 is the initial AR (without latency) in diopters, a represents the amplitude of the response in diopters, x is time in seconds, and τ represents the time constant. The signal is positive for accommodation and negative for disaccommodation.

The Boltzmann sigmoidal model was defined by the function (Fig. 2):

$$Ac = \frac{Af - Ai}{1 + e^{\frac{-(x-x_0)}{w}}} + Ai, \tag{5.6.4}$$

where x is the time in seconds, A_f and A_i are the initial and final asymptotic values, w is the width of the x values between these two asymptotes, and x_0 is located roughly at the centre of w [27].

The response time was defined as the time between the onset of the stimulus step and 98 % of the total change in accommodation when a stable AR is reached [26].

Velocity curves were obtained by taking the first derivative of the fitted function:

$$V(x) = \frac{\partial Ac}{\partial x}, \tag{5.6.4}$$

where V is the velocity of accommodation.

The peak velocity was obtained by solving it when $x = 0$ (Fig. 3) for the exponential model. For the Boltzmann sigmoidal model, the peak velocity of accommodation or disaccommodation corresponds to the maximum or minimum of the derivative function, respectively (Fig. 3) [27].

The root mean square (RMS) deviation was used by several authors to assess the magnitude of the accommodative microfluctuations. This parameter provides the mean level of fluctuation in dioptres around the average AR over a defined period [28,29]. In this study, we also used this metric to assess the accommodative microfluctuations, and it was computed using the following formula:

$$RMSdeviation = \sqrt{\frac{1}{n}\sum (x_i - \overline{x})^2}, \tag{5.6.5}$$

where n is the number of AR taken, xi is each individual AR, and $\overline{x}$ is the average AR.

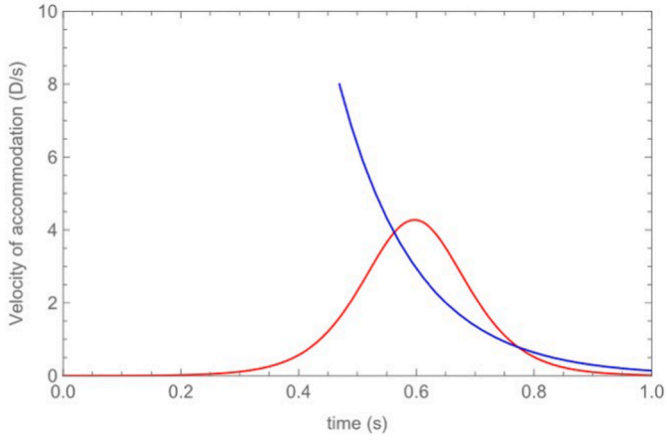

Fig. 3. Accommodation velocity curves when the Boltzmann sigmoidal (red) and the exponential (blue) functions were fitted to the experimental data of one subject for 1.00D of accommodative stimulus. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

All these analyses were carried out using an algorithm developed in version 12.3 of the Wolfram Mathematica software (Wolfram Research, Inc., Champaign, IL (2021)). Statistical analysis was performed using IBM SPSS software, version 29.0.0.0 (IBM Corp., Armonk, NY). The normality of the data was tested using the Shapiro-Wilk test. To compare the means between groups, one-way ANOVA was used for parametric data and Kruskal-Wallis for non-parametric data. To compare the differences between the initial accommodative state and the subsequent stimuli, ANOVA for repeated measures was used for parametric data, and Friedman's test for non-parametric data. Bonferroni correction was performed for multiple comparisons.

3. Results

In this study, 63 eyes of 63 subjects were enrolled and divided into different groups according to their accommodative dysfunction and symptomatology. The number of subjects in each group, their mean age, mean spherical equivalent (SE), the results of the accommodative exams (amplitude of accommodation (AA), lag of accommodation (LA), and facility of accommodation (FA)) performed at the initial eye examination, and the mean CISS score are shown in Table 2.

Age and spherical equivalent were similar in all groups, with no statistically significant differences between them ($p = 0.27$ for age and $p = 0.54$ for spherical equivalent). Concerning the accommodative exams at the initial eye examination: AA was significantly lower in subjects with INSA than in the control group ($p < 0.001$); LA was significantly lower in subjects with EA and higher in subjects with INSA than in the control group ($p = 0.02$ for both); and FA was significantly lower in subjects with INFA ($p < 0.001$), EA ($p < 0.001$), and INSA ($p < 0.001$) than in the control group. The CISS score was significantly higher in the INSA ($p = 0.03$) and SWD ($p < 0.001$) groups. The most common symptom reported by the subjects of the SWD group was "Eyes tired" while reading/doing close work, followed by "Eyes hurt", "Headache", "Difficulty maintaining attention/concentration", "Uncomfortable" and "Trouble remembering ". The other symptoms had an individual score lower than 2.00.

3.1. Accommodative response

The dynamic accommodative and disaccommodative responses over time obtained from wavefront aberrometry for different stimuli are shown in Fig. 4 and the mean values of accommodative response and the residual accommodation for each group are shown in Table 3. As

Table 2
Characteristics (mean ± standard deviation) of the subjects in each group.

	N	Age (years)	SE (D)	AA (D)	LA (D)	FA (cpm)	CISS Score
Control	18	23.9 ± 3.05	0.02 ± 0.30	9.60 ± 1.01	0.57 ± 0.22	14.33 ± 4.38	12.56 ± 4.33
SWD	18	23.2 ± 3.28*	−0.72 ± 1.61*	10.01 ± 2.11*	0.56 ± 0.20*	13.67 ± 4.73*	27.33 ± 2.73†
INFA	6	24.4 ± 5.03*	−0.29 ± 1.32*	8.04 ± 2.64*	0.63 ± 0.38*	3.50 ± 1.97†	19.00 ± 12.26*
EA	9	22.9 ± 3.37*	0.32 ± 0.43*	8.75 ± 1.78*	0.38 ± 0.18†	1.11 ± 2.20†	12.22 ± 6.53*
INSA	12	21.3 ± 4.13*	−0.52 ± 2.81*	5.71 ± 1.29†	0.92 ± 0.33†	7.77 ± 4.51†	20.5 ± 11.39¤
p		*>0.05	*>0.05	*>0.05; †<0.001	*>0.05; †0.02	*>0.05; †<0.001	*>0.05; †<0.001; ¤0.03

*, †, ¤ Comparison to the control group.
N: number of subjects; cpm: cycles per minute; INFA: Infacility of accommodation; EA: Excess of accommodation; INSA: Insufficiency of accommodation; SWD: Symptomatic without dysfunction.
The ± errors indicate the standard deviation from the mean.

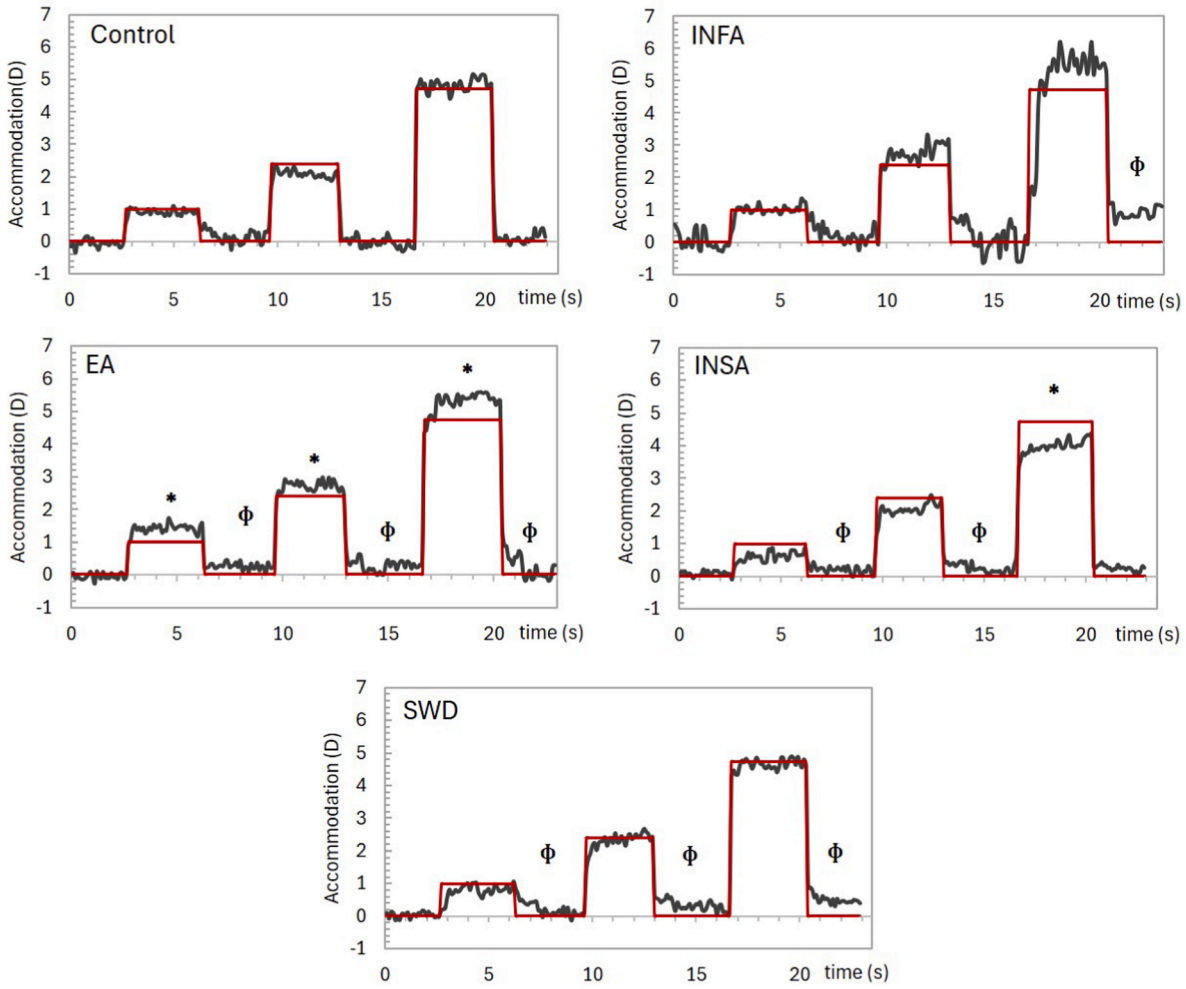

Fig. 4. Accommodative response (black line) over time for the different accommodative stimuli (red line) of the subjects of the different groups: control, INFA, EA, INSA, and SWD.
* Statistically significant difference compared to the control group; ϕ Statistically significant difference compared to the initial state. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

expected, all subjects showed an increase in accommodative response as the accommodative stimulus increased.

The control group presented an accommodative response close to the values of the stimuli (Fig. 4). On the other hand, a mean lead of accommodation was observed in the INFA group for the 2.45 D and 4.73 D stimuli, i.e., the mean accommodative response was higher than the stimuli, but it was not significantly higher than the control group (1.00D, $p = 0.57$; 2.45D, $p = 0.07$; 4.73D, $p = 0.61$). The EA group also showed a mean lead of accommodation for all stimuli, and the accommodative response was significantly higher than the control group for the 1.00D ($p = 0.049$), 2.45D ($p = 0.04$), and 4.73D ($p < 0.01$) stimuli. On the other hand, it is possible to observe a lower accommodative response in the INSA group, which was statistically significantly lower than in the control group for the 4.73D stimulus ($p = 0.02$) but not for the 1.00D ($p = 0.07$) and 2.45D ($p = 0.98$) stimuli. The SWD group had a similar accommodative response to the control group for all accommodative stimuli (1.00D, $p = 0.35$; 2.45D, $p = 0.56$; 4.73D, $p = 0.61$).

Table 3
Mean and standard deviation of accommodation and residual accommodation values of all groups.

	Accommodative response (D)			Residual accommodation (D)		
AS (D)	1.00	2.45	4.73	0.00 (1.00)	0.00 (2.45)	0.00 (4.73)
Control	0.89 ± 0.52	2.08 ± 0.82	4.85 ± 1.10	0.16 ± 0.38ɣ	0.01 ± 0.58ɣ	0.16 ± 0.26ɣ
INFA	0.98 ± 0.12*	2.74 ± 0.33*	5.50 ± 1.64*	0.24 ± 0.18ɣ	0.16 ± 0.34ɣ	0.91 ± 0.20ϕ
EA	1.40 ± 0.13†	2.70 ± 0.50†	5.59 ± 1.36†	0.25 ± 0.21ϕ	0.28 ± 0.23ϕ	0.38 ± 0.02¤
INSA	0.59 ± 0.66*	2.02 ± 0.92*	3.97 ± 0.86¢	0.38 ± 0.35¤	0.34 ± 0.32ϕ	0.25 ± 0.16ɣ
SWD	0.75 ± 0.28*	2.30 ± 0.71*	4.65 ± 0.55*	0.21 ± 0.11¥	0.32 ± 0.20¤	0.50 ± 0.19¥
p	*>0.05; †0.049	*>0.05; †0.04	*>0.05; †0.01; ¢ 0.02	ɣ>0.05; ϕ0.04; ¤0.01; ¥0.03	ɣ>0.05; ϕ0.03; ¤0.01	ɣ>0.05; ϕ0.02; ¤0.01; ¥ 0.03

*; †; ¢ comparison to the control group.
ɣ; ϕ; ¤; ¥ comparison to the initial state.
AS: Accommodative stimulus; INFA: Infacility of accommodation; EA: Excess of accommodation; INSA: Insufficiency of accommodation; SWD: Symptomatic without dysfunction.
The ± errors indicate the standard deviation from the mean.

3.2. Residual accommodation

The subjects of the control group were able to relax accommodation after removing the stimuli and return to their initial state, showing a residual accommodation not significantly different to the initial state (after 1.00D, p = 0.72; 2.45D, p = 0.84; 4.73D, p = 0.41) (Table 2). This behaviour was not found in the other groups. The subjects with INFA were not able to relax the accommodation after the 4.73D stimulus, maintaining a significant residual accommodation when compared to the initial state (1.00D, p = 0.29; 2.45D, p = 0.35; 4.73D, p = 0.02). The EA group had a residual accommodation significantly higher than the initial state after removing all stimuli (1.00D, p = 0.04; 2.45D, p = 0.03; 4.73D, p = 0.01). The subjects with INSA were also unable to relax accommodation after removing the 1.00D and 2.45D stimuli, with values of residual accommodation significantly higher than the initial state (1.00D, p = 0.01; 2.45D, p = 0.03; 4.73D, p = 0.10). In the SWD group, residual accommodation was significantly higher than the initial state after the 1.00D (p = 0.03), 2.45D (p = 0.01), and 4.73D (p = 0.03) stimuli were removed.

3.3. Microfluctuations of accommodative response and residual accommodation

The microfluctuations of accommodation were assessed by RMS deviation. Fig. 5 shows the differences between its value at each accommodative state and the initial value. The control, EA, and INFA groups show no significant changes in microfluctuations between the initial state and during the 1.00D (control, p = 0.54; EA, p = 0.54; INFA, p = 0.70), 2.45D (control, p = 0.54; EA, p = 0.08; INFA, p = 0.25) and 4.73D (control, p = 0.15; EA, p = 0.66; INFA, p = 0.44) stimuli. On the other hand, the INSA group had a significant increase in microfluctuations during the 1.00D (p = 0.001), 2.45D (p = 0.03), and 4.73D (p = 0.03) accommodative stimuli. The same was observed in the SWD group, with a significant increase during the 1.00D (p = 0.03), 2.45D (p = 0.048), and 4.73D (p = 0.047) accommodative stimuli.

The microfluctuations of residual accommodation (Fig. 5) of the control and EA groups showed no significant differences between the initial state and after removing the 1.00D (control, p = 0.54; EA, p = 0.46), 2.45D (control, p = 0.84; EA, p = 0.31), and 4.73D (control, p = 0.68; EA, p = 0.31) stimuli. The INFA group had significantly higher microfluctuations after the 2.45D (p = 0.04) stimulus was removed

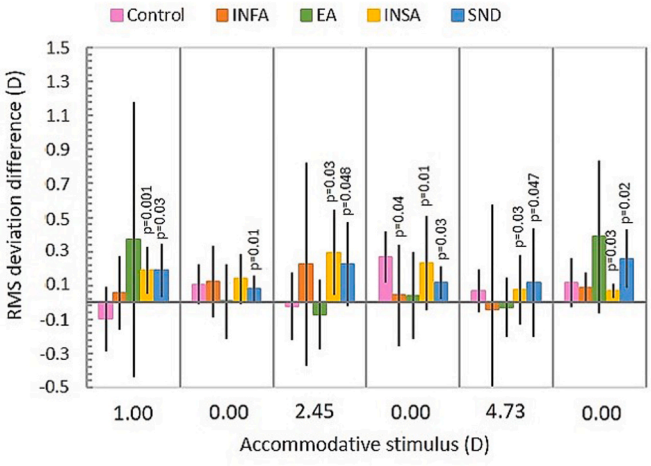

Fig. 5. Differences in RMS deviation of microfluctuations between the accommodative response and the residual accommodation and the initial state. Error bars are the confidence intervals for 95 %. p-values represent statistically significant differences between the value for each stimulus and the initial value.

when compared to the initial state, but not after the 1.00D (p = 0.50) and 4.73D (p = 0.83) stimuli. The INSA group showed significantly higher values after removing the 2.45D (p = 0.01) and 4.73D (p = 0.03) stimuli compared to the initial state, but not after the 1.00D (p = 0.18) stimulus. The SWD group had significantly higher values after the 1.00D (p = 0.03), 2.45D (p = 0.03), and 4.73D (p = 0.02) stimuli were removed compared to the initial state.

3.4. Accommodative and disaccommodative response times

Accommodative and disaccommodative response times of each group are shown in Table 4. Differences in response time were observed between the control group and the INFA, EA, INSA, and SWD groups for some accommodative conditions. The INFA group had a significantly slower accommodative response than the control group at 2.40D (p = 0.03) and 4.73D (p = 0.045) accommodative stimuli, but not at 1.00D (p = 0.81). SWD also had a slower accommodative response for the 1.00D (p = 0.046) and 2.45D (p = 0.048) accommodative stimuli, but no significant differences for the 4.73D stimulus (p = 0.76). On the other hand, the EA group had a significantly faster accommodative response at 1.00D of accommodative stimulus (p = 0.045), but with no significant differences at 2.45D (p = 0.79) and 4.73D (p = 0.99). The INSA group had no significant differences compared to the control group at any stimulus (1.00D, p = 0.56; 2.45D, p = 0.09; 4.73D, p = 0.99).

Regarding disaccommodation response, the INFA group had slower disaccommodation than the control group after the 1.00D (p = 0.03) and 2.40D (p = 0.01) stimuli, but no significant differences after 4.73D (p = 0.85). On the other hand, the EA group showed significant differences only after the 4.73D stimulus (1.00D, p = 0.89; 2.45D, p = 0.99; 4.73D, p = 0.048). The INSA group had a significantly slower disaccommodation only after the 2.45D stimulus (1.00D, p = 0.68; 2.45D, p = 0.02; 4.73D, p = 0.95), and the SWD group after the 1.00D stimulus (1.00D, p = 0.048; 2.45D, p = 0.51; 4.73D, p = 0.63).

3.5. Peak velocity of accommodative and disaccommodative responses

Table 5 shows the peak velocity of accommodative and disaccommodative responses for the 1.00D, 2.45D, and 4.73D stimuli. The results show that the peak velocity of accommodative and disaccommodative responses changes significantly between the INFA, EA, INSA, and SWD groups and the control group for some levels of accommodative and disaccommodative stimuli. The INFA group shows a significantly lower peak velocity than the control group at 4.73D

Table 4
Mean and standard deviation of accommodative and disaccommodative response times for the different cycles of accommodation and disaccommodation of the control, INFA, AE, INSA, and SWD groups.

	Response time (ms)					
	Accommodative response			Disaccommodative response		
Accommodative stimulus (D)	1.00	2.45	4.73	0.00 (1.00)	0.00 (2.45)	0.00 (4.73)
Control	708 ± 194	456 ± 273	504 ± 46	933 ± 554	535 ± 251	450 ± 148
INFA	700 ± 560*	698 ± 161†	1453 ± 154†	2170 ± 316†	2821 ± 425†	501 ± 335*
EA	445 ± 149†	376 ± 162*	631 ± 211*	769 ± 712*	1011 ± 428*	1170 ± 200†
INSA	1000 ± 309*	535 ± 339*	483 ± 241*	573 ± 354*	2220 ± 501¤	712 ± 429*
SWD	1042 ± 274¤	926 ± 355¤	494 ± 275*	2771 ± 568¤	1009 ± 548*	635 ± 228*
p	*>0.05; †0.045; ¤0.046	*>0.05; †0.03; ¤0.048	*>0.05; †0.045	*>0.05; †0.03; ¤0.048	*>0.05; †0.01; ¤0.02	*>0.05; †0.048

*; † comparison with the control group.
The ± errors indicate the standard deviation from the mean.

Table 5
Mean peak velocity of accommodative and disaccommodative responses for the 1.00D, 2.45D, and 4.73D accommodative stimuli.

	Peak velocity (D/s)					
	Accommodative response			Disaccommodative response		
Accommodative stimulus (D)	1.00	2.45	4.73	0.00 (1.00)	0.00 (2.45)	0.00 (4.73)
Control	5.47 ± 1.75	13.24 ± 1.69	13.68 ± 1.20	1.63 ± 1.24	8.93 ± 1.26	12.32 ± 0.40
INFA	4.33 ± 0.62	14.12 ± 1.02	9.51 ± 0.99*	2.01 ± 0.65	8.19 ± 2.02	11.03 ± 2.01
AE	13.58 ± 2.10*	15.77 ± 2.95	10.60 ± 3.31	12.00 ± 0.12	6.90 ± 0.25*	5.99 ± 1.54*
INSA	2.39 ± 1.55	9.29 ± 2.97	10.84 ± 1.05†	5.14 ± 3.00	4.30 ± 2.50†	13.16 ± 1.85
SWD	1.84 ± 0.52†	13.39 ± 1.39	6.70 ± 0.22¢	1.36 ± 0.40	9.42 ± 1.89	9.85 ± 0.98†
p	*0.046; †0.04	>0.05	*0.048; †0.04; ¢0.02	>0.05	*0.03; †0.048	*0.04; †0.047

*; †; ¢ statistically significant compared to the control group.
The ± errors indicate the standard deviation from the mean.

accommodative stimulus ($p = 0.048$), indicating a limitation of these subjects to achieve high velocities for high accommodative stimuli. The AE group achieved high velocities of accommodative response, with significantly higher values for the 1.00D stimulus ($p = 0.046$), whereas it was difficult to achieve high velocities of disaccommodation after the 2.45D ($p = 0.03$) and 4.73D ($p = 0.04$) stimuli. The INSA group shows significantly lower peak velocity of accommodative response at 4.73D stimulus ($p = 0.04$) and in disaccommodative response after the 2.45D stimulus ($p = 0.048$). The SWD group also had significantly lower peak velocities of accommodative response at 1.00D ($p = 0.04$) and 4.73D ($p = 0.02$) and in disaccommodative response after the 4.73D stimulus ($p = 0.047$).

The findings related to accommodative and disaccommodative responses, residual accommodation, and their microfluctuations, response times, and peak velocities in each group of subjects were summarized and shown in Table 6. These signals are based on statistically significant differences found compared to their initial state and the control group and show specific patterns of the characteristics of dynamic accommodation and disaccommodation associated with each type of disorder.

4. Discussion

In this study, wavefront sensing was used to objectively assess the dynamic accommodation of subjects with accommodative dysfunctions (INFA, INSA, and EA) as well as subjects who experience symptoms related to near vision tasks but who have not been diagnosed with any accommodative dysfunction (SWD). The latter group primarily reported complaints such as “Eyes tired” while reading/doing close work, followed by “Eyes hurt”, “Headache”, “Difficulty maintaining attention/concentration”, “Uncomfortable” and “Trouble remembering“, as detailed in the results section. Previous studies have identified these visual symptoms as factors that can significantly impact daily life and diminish both academic and professional performance [30,31].

Accommodative and disaccommodative responses were assessed for various cycles of accommodation and disaccommodation stimuli,

Table 6
Signals of dynamic accommodation found in subjects with INFA, AE, INSA and SWD. Initial state refers to the initial relaxed state before the stimuli.

			INFA	EA	INSA	SWD
Signals	Accommodative response		Without significant changes	↑ control and stimuli	↓ control and stimuli	Without significant changes
	Residual accommodation		↑ than initial state	↑ than initial state	↑ than initial state	↑ than initial state
	Microfluctuations	Accommodative response	Without significant changes	Without significant changes	↑ than initial state	↑ than initial state
		Residual accommodation	↑ than initial state	Without significant changes	↑ than initial state	↑ than initial state
	AR time	Accommodative response	↑ control	↓ control	Without significant changes	↑ control
		Residual accommodation	↑ control	↑ control	↑ control	↑ control
	Peak velocity	Accommodative response	↓ control	↑ control	↓ control	↓ control
		Residual accommodation	Without significant changes	↓ control	↓ control	↓ control

revealing characteristics distinct from those of the control group and significant alterations compared to their initial state.

Subjects with INFA had significantly slower accommodative responses for 2.45D and 4.73D stimuli and took more time to relax accommodation and stabilize it after 1.00D and 2.45D stimuli than the control group. For the 4.73D stimulus, these subjects were unable to completely relax accommodation, resulting in a residual accommodation that was significantly higher than the initial value and the value of the control group. This is to be expected in subjects who usually have more difficulty with the positive lens in the flipper test. During disaccommodative response after this stimulus, a stable value was achieved in a shorter time, despite incomplete relaxation of accommodation, which explains the non-statistically significant difference in the response time for this stimulus. A previous study shows that time for disaccommodation may also be a predictor of accommodative facility [32]. However, it is important to check that the subjects actually reach their state of accommodation relaxation.

INFA is usually diagnosed based on the accommodative facility test, which assesses only at far and one demand at near. The method we presented not only provides the response times but also allows observation of the facility of accommodation for additional demands. This is very important for INFA, as it involves difficulty in changing focus quickly and accurately across different demands, which could not be fully assessed using traditional methods and the method we propose provides this novel advantage. The peak velocity for 4.73D also indicates that these subjects cannot reach high velocities of accommodative response for high stimuli. The significant increase in microfluctuations observed in the residual accommodation after the 2.45D stimulus reveals an increase in accommodative instability. This may explain the intermittent focusing sometimes reported by these subjects during the accommodative facility test with the +2.00D lens at near vision, which may lead to erroneous results if the patient considers it as "clear" despite noticing unstable clarity. They may have unstable accommodation and as a result may show a higher accommodative facility than it actually is.

For the EA group, the excessive accommodative response and residual accommodation to all stimuli are notable. These subjects not only accommodated more than the stimuli required but were also unable to relax accommodation to its initial value after stimulation. This is expected, as subjects with EA are characterized by presenting leads of accommodation. The method presented allows us to observe that the EA is characterized by fast accommodative responses, reaching high velocities, but slower disaccommodative responses and difficulty in relaxing accommodation, with disaccommodation becoming slower as the stimulus increases. Subjects with EA have accommodative responses higher than the expected values for various accommodative demands, which cannot be observed in the clinical exams, which are only performed for 2.50D demand. Furthermore, subjects with EA in the early stages may only have difficulty relaxing their accommodation after higher stimuli (more than 2.50D), as the differences found were pronounced for higher stimuli. The method we present is a new way of detecting accommodative responses that are higher than expected for different accommodative demands, which is important for subjects who may present leads of accommodation for distances closer of farther than 40 cm. On the other hand, the microfluctuations of accommodation do not seem to be affected by EA.

The INSA group had the lowest accommodative response for all stimuli, being significantly lower than the control group for the 4.73D stimulus. This is expected, as subjects with INSA have lower amplitude of accommodation. Given their young age, it was expected to find no significant differences for low stimuli even with INSA. However, after the 1.00D and 2.45D stimuli, they were unable to fully relax their accommodation, showing significant residual accommodation compared to the initial value. Contrary to previous studies using clinical examinations, in which the −2.00D lens was found to be more difficult in the near-vision accommodative facility test, we observed that they also have difficulty in relaxing accommodation, likely due to the excessive effort made by these subjects to keep the target in focus. This is particularly evident after the 2.45D stimulus. This highlights how dynamic accommodation assessment can reveal relaxation difficulties not typically detected in the current clinical exams. These subjects were also unable to achieve high velocities of accommodation and disaccommodation. The observed significant increase in microfluctuations of accommodation for all accommodative stimuli is probably due to their difficulty in accommodating, leading to greater instability in the accommodative response, which is also observed after the highest stimulus (4.73D). A previous study [33] indicates that microfluctuations of accommodation are more pronounced in individuals with thinner ciliary bodies. Given that subjects with accommodative dysfunctions exhibit increased microfluctuations during accommodation, the thickness of the ciliary body may be related to the development of some accommodative dysfunctions.

The changes observed in dynamic accommodation are particularly interesting in the SWD group. These subjects had normal clinical examinations but reported symptoms related to near tasks, with a CISS score higher than 21, which was significantly higher than the control group. When dynamic accommodation is analysed for the different cycles of accommodation and disaccommodation, these subjects show difficulty to disaccommodate, with similar behaviour observed in subjects with accommodative dysfunctions. Their residual accommodation was significantly higher than both the initial values and those of the control group. If these subjects are on the verge of developing an accommodative dysfunction, some of them could present an accommodative response slightly higher and lower than the stimuli (for 1.00D, 2.45D, and 4.73D) and than the control group, resulting in an average close to the stimulus, which could explain their non-significant difference with the control group. In addition, their response times were slower than those of the control group, with peak velocities reaching lower values for certain demands. Furthermore, the significant increase in accommodative microfluctuations indicates instability in the accommodative response during all stimuli and in the residual accommodation after the stimuli are removed. These novel insights provides a potential explanation for the symptoms reported by these subjects, which are very common in those who spend a lot of time in near vision [34,35].

Another finding is the non-linearity of the peak velocity with the accommodative response amplitude in the subjects with accommodative dysfunctions and SWD, observed by previous studies [6]. Peak velocities are influenced by the starting point of the response [6,36], which varied for disaccommodation in our study. This variability, along with the presence of dysfunctional accommodative responses, may explain the non-linearity of peak velocity.

The assessment of dynamic accommodation allows real-time monitoring of the accommodative behaviour when changing between different distances. This provides a closer representation of the accommodative performance in everyday situations compared to static measurements and gives us more detailed information about the accommodative response. According to previous studies [37,38], many subjects perform near vision tasks at distances shorter than 40 cm, so it is important to analyse the accommodative response at distances beyond this, which is the only distance analysed in clinical exams.

Some accommodative disorders may not be apparent through static testing, but the assessment of dynamic accommodation using the method we present can reveal issues that may otherwise be missed. Additionally, wavefront measurement provides objective and quantitative data, reducing reliance on subjective patient responses. This method may be a new way to improve the diagnosis of accommodative dysfunctions and allow for their detection at early stages, perhaps before symptoms manifest. Detailed information from dynamic accommodation evaluation may assist eye care professionals in selecting the most appropriate treatment for patients, for instance, to reduce the accommodative response, improve the response time, or reduce the

microfluctuations of accommodation, tailored to each patient's specific accommodative issues. Moreover, it may also help professionals tailor treatment plans, such as vision therapy plans, for more effective follow-up. The results suggest a commercial and clinical potential of this method to assist and improve the diagnosis and follow-up of such conditions.

The study also has important limitations that also should be discussed. It is important to note that the measurements were made under monocular rather than binocular viewing conditions. Performing the measurements monocularly would miss the effect of convergence. According to a previous study the objective measurements of accommodation using the Shack-Hartmann wavefront sensor may show higher values compared to the monocular viewing condition [39]. This could be a limitation of our results. However, this difference between monocular and binocular accommodation is particularly problematic in exophoric and esophoric subjects [40], which were not included in our study. Moreover, in clinical practice, the amplitude and facility of accommodation are also usually measured monocularly. This issue might also be mitigated if we consider that this effect is present in all subjects, including the control group.

Another limitation of our study is the sample size of some groups, especially the INFA group. It is important to emphasise that the results of this group in particular should be carefully analysed when extended to the general population and should be considered as preliminary results. Future studies should use larger and more balanced samples of subjects with accommodative dysfunction to increase statistical power, improve reliability and increase the validation of the results.

The participants near work habits were a missing information in our study. Future studies should collect this data to investigate the relationship between near work habits, symptoms and changes in the characteristics of the dynamic accommodative response. This could include assessing dynamic accommodation in subjects with different near work habits, or assessing it after tasks performed at different distances and with different demands. Such research may provide insights into how specific work habits affect accommodative function and help to identify early markers that may lead to specific accommodative dysfunctions and symptoms.

We also suggest to carry out longitudinal studies to investigate whether dynamic accommodative assessment methods detect early signs of accommodative dysfunctions before symptoms become apparent, i.e. which subjects are at risk of developing accommodative dysfunction and related symptoms, and how these findings correlate with the onset of clinical symptoms. Assessing these accommodative parameters and following subjects over time to observe which of them develop these issues would be interesting for further exploration of this topic. Another suggestion might be to follow-up patients over time and observe the effects of tailored interventions, such as vision therapy or optical corrections, on these dynamic accommodative parameters.

Other methods of continuous measurement of the accommodative response, such as continuous photorefraction, should be explored for the same applicability.

CRediT authorship contribution statement

Jessica Gomes: Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis. **Sandra Franco:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Ethics statement

The authors declare that all procedures were performed in compliance with relevant laws and institutional guidelines and have been approved by the Ethics Committee for Research in Life and Health Sciences (CEICVS) from the University of Minho.

The study adhered to the tenets of the Declaration of Helsinki and was approved by the Ethics Committee for Research in Life and Health Sciences of the University of Minho (SECVS 029/2014 (ADENDA), July 2, 2019). All subjects signed an informed consent with an explanation of the procedures. This explanation consisted of a brief description of the technical procedures of the exams.

Funding

This research was funded by the Portuguese Foundation for Science and Technology (FCT) in the framework of the Strategic Funding UIDB/04650/2020. The author J.G. is also supported by the PhD grant 2020.08737. BD from FCT.

Declaration of competing interest

None declared.

References

[1] F. Sun, L. Stark, Dynamics of accommodation: measurements for clinical application, Exp. Neurol. 91 (1986) 71–79, https://doi.org/10.1016/0014-4886(86)90027-0.
[2] S. Phillips, L. Stark, Blur: a sufficient accommodative stimulus, Doc. Ophthalmol. 43 (1977) 65–89, https://doi.org/10.1007/BF01569293.
[3] D.M. Win-Hall, J. Houser, A. Glasser, Static and dynamic accommodation measured using the WAM-5500 autorefractor, Optom. Vis. Sci. 87 (2010) 873–882, https://doi.org/10.1097/OPX.0b013e3181f6f98f.
[4] G. Heron, B. Winn, Binocular accommodation reaction and response times for normal observers, Ophthalmic Physiol. Opt. 9 (1989) 176–183, https://doi.org/10.1111/j.1475-1313.1989.tb00839.x.
[5] J. Tucker, W.N. Charman, Reaction and Response times for accommodation, Am. J. Optom. Physiol. Opt. 56 (1979) 490–503, https://doi.org/10.1097/00006324-197908000-00003.
[6] S.R. Bharadwaj, C.M. Schor, Dynamic control of ocular disaccommodation : first and second-order dynamics, Vis. Res. 46 (2006) 1019–1037, https://doi.org/10.1016/j.visres.2005.06.005.
[7] N. Lupón, J. Gispets, G. Cardona, A. Tàpia, H. Abril, Role of microfluctuations in accommodation: a novel approach to reduce non-accommodative noise, Int. J. Ophthalmol. 12 (2019) 681–684, https://doi.org/10.18240/ijo.2019.04.25.
[8] W.N. Charman, G. Heron, Microfluctuations in accommodation: an update on their characteristics and possible role, Ophthalmic Physiol. Opt. 35 (2015) 476–499, https://doi.org/10.1111/opo.12234.
[9] S. Plainis, H.S. Ginis, A. Pallikaris, The effect of ocular aberrations on steady-state errors of accommodative response, J. Vis. 5 (2005), https://doi.org/10.1167/5.5.7.
[10] J. Tarrant, A. Roorda, C.F. Wildsoet, Determining the accommodative response from wavefront aberrations, J. Vis. 10 (2010) 1–16, https://doi.org/10.1167/10.5.4.
[11] J. Liang, B. Grimm, S. Goelz, J. Bille, Objective measurement of wave aberrations of the human eye with the use of a Hartmann–Shack wave-front sensor, J. Opt. Soc. Am. A 11 (1994) 1949–1957, https://doi.org/10.1364/josaa.11.001949.
[12] X. Yu, Y. Dai, X. Rao, C. Wang, L. Xue, W. Jiang, Y. Xiong, A wavefront aberrometer for dynamic high-order aberration measurement, Optik 121 (2010) 1405–1411, https://doi.org/10.1016/j.ijleo.2009.02.023.
[13] V.M. Hernandez, M. Ruggeri, F. Manns, J.-M.A. Parel, Measurement of accommodation with high dynamic range using a shack-hartmann wavefront sensor and dual channel accommodation stimulus, Invest. Ophthalmol. Vis. Sci. 56 (2015) 6010.
[14] K.M. Hampson, S.S. Chin, E.A. Mallen, Dual wavefront sensing channel monocular adaptive optics system for accommodation studies, Opt Express 17 (2009) 18229–18240, https://doi.org/10.1364/OE.17.018229.
[15] C.E. García-Guerra, J.A. Martínez-Roda, J.C. Ondategui-Parra, A. Turull-Mallofré, M. Aldaba, M. Vilaseca, System for objective assessment of the accommodation response during subjective refraction, Transl. Vis. Sci. Technol. 12 (2023) 1–11, https://doi.org/10.1167/tvst.12.5.22.
[16] P. Cacho-Martínez, Á. García-Muñoz, M.T. Ruiz-Cantero, Do we really know the prevalence of accomodative and nonstrabismic binocular dysfunctions? J. Opt. 3 (2010) 185–197, https://doi.org/10.1016/S1888-4296(10)70028-5.
[17] S. Franco, A. Moreira, A. Fernandes, A. Baptista, Accommodative and binocular vision dysfunctions in a Portuguese clinical population, J. Opt. 15 (2022) 271–277, https://doi.org/10.1016/j.optom.2021.10.002.
[18] S.E. Doherty, L.A. Doyle, S.J. McCullough, K.J. Saunders, Comparison of retinoscopy results with and without 1% cyclopentolate in school-aged children, Ophthalmic Physiol. Opt. 39 (2019) 272–281, https://doi.org/10.1111/opo.12629.
[19] P. Sankaridurg, X. He, T. Naduvilath, M. Lv, A. Ho, E. Smith, P. Erickson, J. Zhu, H. Zou, X. Xu, Comparison of noncycloplegic and cycloplegic autorefraction in categorizing refractive error data in children, Acta Ophthalmol. 95 (2017) e633–e640, https://doi.org/10.1111/aos.13569.

[20] N.S. Yeotikar, R.C. Bakaraju, P.S.R. Reddy, K. Prasad, Cycloplegic refraction and noncycloplegic refraction using contralateral fogging: a comparative study, J. Mod. Opt. 54 (2007) 1317–1324, https://doi.org/10.1080/09500340600855346.
[21] F. Lara, P. Cacho, Á. García, R. Megías, General binocular disorders: prevalence in a clinic population, Ophthalmic Physiol. Opt. 21 (2001) 70–74, https://doi.org/10.1046/j.1475-1313.2001.00540.x.
[22] C. Darko-Takyi, A. Owusu-Ansah, F. Boampong, E.K. Morny, F. Hammond, S. Ocansey, Convergence insufficiency symptom survey (CISS) scores are predictive of severity and number of clinical signs of convergence insufficiency in young adult Africans, J. Opt. 15 (2022) 228–237, https://doi.org/10.1016/j.optom.2021.05.001.
[23] S. Kasthurirangan, A. Glasser, Dynamics of accommodation and disaccommodation from various starting points, Invest. Ophthalmol. Vis. Sci. 47 (2006) 3894.
[24] D.A. Atchison, S.R. Varnas, Accommodation stimulus and response determinations with autorefractors, Ophthalmic Physiol. Opt. 37 (2017) 96–104, https://doi.org/10.1111/opo.12340.
[25] L.N. Thibos, X. Hong, A. Bradley, R.A. Applegate, Accuracy and precision of objective refraction from wavefront aberrations, J. Vis. 4 (2004) 329–351, https://doi.org/10.1167/4.4.9.
[26] S.S. Chin, Adaptive Optics, Aberration Dynamics and Accommodation Control, University of Bradford, 2009.
[27] A.J. Del Águila-Carrasco, J.J. Esteve-Taboada, E. Papadatou, T. Ferrer-Blasco, R. Montés-Micó, Amplitude, latency, and peak velocity in accommodation and disaccommodation dynamics, BioMed Res. Int. 2017 (2017), https://doi.org/10.1155/2017/2735969.
[28] H.A. Anderson, A. Glasser, R.E. Manny, K.K. Stuebing, Age-related changes in accommodative dynamics from preschool to adulthood, Investig. Ophthalmol. Vis. Sci. 51 (2010) 614–622, https://doi.org/10.1167/iovs.09-3653.
[29] L. Gray, B. Winn, B. Gilmartin, Effect of target luminance on microfluctuations of accommodation, Ophthalmic Physiol. Opt. 13 (1993) 258–265, https://doi.org/10.1111/j.1475-1313.1993.tb00468.x.
[30] C. Alvarez-Peregrina, M.Á. Sánchez-Tena, C. Andreu-Vázquez, C. Villa-Collar, Visual health and academic performance in school-aged children, Int. J. Environ. Res. Publ. Health 17 (2020), https://doi.org/10.3390/ijerph17072346.
[31] C. Kovarski, S. Portalier, C. Faucher, C. Carlu, D. Bremond-Gignac, C. Orssaud, Effects of visual disorders on the academic achievement of French secondary school students, Arch. Pediatr. 27 (2020) 436–441, https://doi.org/10.1016/j.arcped.2020.08.013.
[32] N. Szostek, H. Buckhurst, C. Purslow, T. Drew, A. Collinson, P. Buckhurst, Validation of novel metrics from the accommodative dynamic profile, Vision 34 (2018), https://doi.org/10.3390/vision2030034.
[33] K.E. Schultz, L.T. Sinnott, D.O. Mutti, M.D. Bailey, Accommodative fluctuations, lens tension, and ciliary body thickness in children, Optom. Vis. Sci. 86 (2009) 677–684, https://doi.org/10.1097/OPX.0b013e3181a7b3ce.Accommodative.
[34] J.R. Hayes, J.E. Sheedy, J.A. Stelmack, C.A. Heaney, Computer use, symptoms, and quality of life, Optom. Vis. Sci. 84 (2007) 738–755, https://doi.org/10.1097/OPX.0b013e31812f7546.
[35] A. Rossignol, E. Morse, V. Summers, L. Pagnotto, Video display terminal use and reported health symptoms among Massachusetts clerical workers, J. Occup. Med. Off. Publ. Ind. Med. Assoc. 29 (1987) 112–118.
[36] S. Kasthurirangan, A. Glasser, Influence of amplitude and starting point on accommodative dynamics in humans, Invest Ophthalmol Vis SciVis Sci. 46 (2005) 3463–3472, https://doi.org/10.1167/iovs.10-5269.
[37] S. Gajjar, L.A. Ostrin, A systematic review of near work and myopia : measurement, relationships, mechanisms and clinical corollaries, Acta Ophthalmol. 100 (2022) 376–387, https://doi.org/10.1111/aos.15043.
[38] K. Panke, L. Jakobsone, A. Svede, G. Krumina, Smartphone viewing distance during active or passive tasks and relation to heterophoria, in: Proc. SPIE 11207, Fourth Int. Conf. Appl. Opt. Photonics, 2019, https://doi.org/10.1117/12.2527313.
[39] T. Fujikado, H. Kanda, T. Morimoto, M. Hirota, Difference of accommodative response between binocular and monocular viewing condition measured by binocular wavefront sensor, Invest. Ophthalmol. Vis. Sci. 60 (2019) 1790.
[40] H. Momeni-Moghaddam, D.A. Goss, M. Sobhani, Accommodative response under monocular and binocular conditions as a function of phoria in symptomatic and asymptomatic subjects, Clin. Exp. Optom. 97 (2014) 36–42, https://doi.org/10.1111/cxo.12074.