

Simultaneous Measurement of Objective and Subjective Accommodation in Response to Step Stimulation

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PURPOSE. This study aimed to evaluate differences in objective and subjective accommodation dynamically and simultaneously.

METHODS. Thirty-four pre-presbyopic healthy volunteers (mean age \pm SD, 41.0 \pm 3.2 years) participated in this study. Initially, the reaction time for detecting a change in the target was measured at near. Dynamic accommodation was then monocularly recorded using an open-view Shack–Hartmann aberrometer and compared with the amplitude and velocity of subjective accommodation.

RESULTS. The objective amplitude of accommodation (0.97 \pm 0.32 diopter [D]) was significantly greater than the subjective amplitude of accommodation (0.62 \pm 0.43 D; $P < 0.001$). The accommodative velocity was significantly faster for the “before the accommodation” response time (0.47 \pm 0.38 D/s) than the “after the accommodation” response time (0.21 \pm 0.22 D/s; $P = 0.007$).

CONCLUSIONS. The human eye under the monocular condition quickly adjusts to the focal plane to clearly archive the nearby object, and the focal plane thereafter is slowly and accurately adjusted to the visual target after visual recognition.

Keywords: accommodation, presbyopia, pupils

Ocular accommodation refers to the ability of the eye to focus on objects at a close distance.¹ The optical power of the eye shifts myopic degrees when the focus plane changes from far to near (accommodation) to correct for the defocused retinal image, such that the axial crystalline lens thickness and lens power increase.^{2–4} In contrast, the optical power of the eye returns to its natural state when the focus plane changes from near to far (disaccommodation).

An infrared optometer (autorefractometer) can be used to evaluate accommodation dynamics objectively and continuously.³ The outcome of accommodation relates to age, refractive status, and the quality of the accommodative stimulus. With regard to the analysis of pulse changes in accommodation demand, the accommodative response to a stimulus can be attributed to the nonlinear behavior of one or more component elements such as accommodative peak velocity or the amplitude of accommodation.^{5–7} Several studies that modeled the accommodative response used techniques such as exponential fitting and sigmoidal fitting because the optical power of the eye shows a quick and large change at first that thereafter gradually slows.^{8–11} The mechanism by which the optical power of the eye undergoes nonlinear changes is not clearly understood.

Although objective and subjective amplitudes of accommodation significantly correlate with each other, the objective amplitude of accommodation measured by an autorefractor is significantly smaller than the subjective ampli-

tude of accommodation.¹² In addition to understanding the difference between subjective and objective accommodative amplitudes,¹³ it is important to understand their dynamic differences, because one of the early symptoms of presbyopia is the prolonged time required to focus on a near target. Therefore, the aim of the present study was to measure the amplitude and dynamics of subjective and objective accommodation in pre-presbyopes.

METHODS

Subjects

Thirty-four pre-presbyopic middle-aged healthy volunteers (17 females, 17 males: mean age \pm SD, 41.0 \pm 3.2 years; age range, 35–48 years) participated in this study. Subjects were excluded if their vision was blurred at 50 cm when examined using the push-up method for evaluating best-corrected visual acuity at a distance. In all participants, ocular dominance for distance was determined at baseline using the hole-in-card test.

Only the dominant eye was subjected to subjective and objective measurements. The distance (5.0 m) refractions of the subjects were obtained using a custom-made binocular open-view Shack–Hartmann wavefront aberrometer (BWFA; Topcon Corp., Tokyo, Japan). The amplitude of

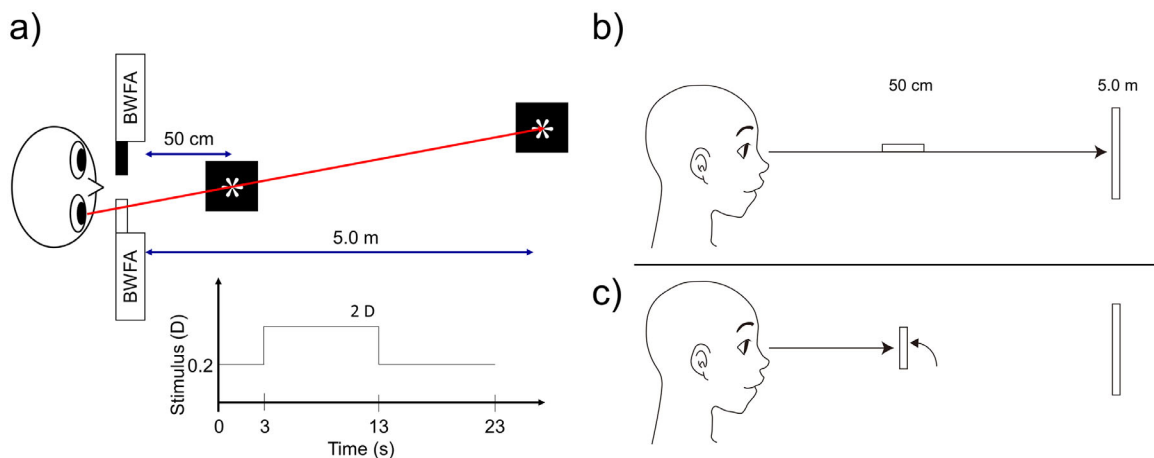


FIGURE 1. Experimental environments. (a) The subject's gaze was set to be straight when looking at the distant and near targets to avoid convergence accommodation. The transmittance of the liquid crystal shutter for the nondominant eye was set at 0.07% (complete darkness) during measurement. (b, c) The distant target was displayed for 3 seconds, and then the target was changed from distant to near for 10 seconds. Subsequently, the target was changed from near to distant for 10 seconds. All subjects were instructed to press the button when the target looked clear, subjectively, after it was switched from distant to near or near to distant. BWFA, binocular open-view Shack-Hartmann wavefront aberrometer.

accommodation represents the difference between the distance and near spherical equivalent (SE) refractions.

The nature and possible complications of the study were explained to all subjects, and each of them provided written informed consent. This investigation adhered to the tenets of the Declaration of Helsinki. The experimental protocol and consent procedures were approved by the Institutional Review Board of Osaka University Medical School (15294-4).

Evaluating Objective Accommodation

Apparatus. The objective accommodation was measured using the BWFA with 840-nm infrared light.^{14,15} The BWFA was equipped with an eye-tracking system used to monitor the pupil and corneal reflection with 940-nm infrared light. Moreover, this instrument measured and recorded ocular refraction simultaneously at a sampling rate of 30 Hz (Supplementary Video S1). Liquid-crystal shutters (X-FOS(G2)-CE, 2×2; LC-Tec Displays AB, Borlänge, Sweden) were placed between the BWFA and the eyes of the subject. The liquid-crystal shutter was used to occlude the nondominant eye.

Fixation Targets. In this study, we adopted step stimulation to record the ocular refractive changes. For distance (5.0 m), the subject fixated at an asterisk target that was equivalent to a 20/200 (87.3 mm) distance eye chart letter. To maintain alignment of the subject's gaze, the near (50 cm) asterisk target, which was equivalent to a 20/200 (8.73 mm) near eye chart letter, was flipped in front of the distant target (Fig. 1, Supplementary Video S2). The subject's gaze was set to be straight when looking at the distant and near targets to avoid convergence response (Fig. 1). Showing and hiding the near target were controlled by a personal computer with a Windows operating system (Microsoft, Redmond, WA, USA) linked with the BWFA using the transistor–transistor logic (TTL) signal.

Evaluating the Subjective Response

Each subject was asked to press a button for each visual task. When the subject pressed the button, a signal was sent to the

computer board (Arduino UNO Rev3; Arduino, Turin, Italy) of a personal computer to initiate the TTL signal to apply a time stamp and control the position of the near target.

Measurement of Reaction Time to Calibrate Subjective Response Time

The subject, with distance correction in place, fixated on the center of a white target cross on a gray background at 50 cm and then immediately pressed the button after the fixation target changed from a cross to an asterisk. The time between when the target was displayed and when the button was pressed was the reaction time.¹⁶ Using the criteria described by Brenner and Smeets,¹⁷ the target switching time was varied randomly between 2 and 5 seconds (Supplementary Video S3). An algorithm written with Python 3.6.5 was used to record the reaction times. In the analysis, each subject's reaction time was defined as the median of 20 separate measurements.

Measurements of Objective and Subjective Accommodation

The transmittance of the liquid crystal shutter for the nondominant eye was set to 0.07% during all measurements (complete darkness). SE refraction and pupil diameter were measured continuously while the distant target was displayed for 3 seconds; the target distance was subsequently changed from distant to near for 10 seconds and then from near to distant for 10 seconds. The illumination of the room was set to 270 lux using an illuminometer (LM-331; AS ONE Corp., Osaka, Japan).

All subjects were instructed to press the button when the target looked clear, subjectively, after the targets were switched from distant to near or near to distant. Each subject performed this procedure five times.

Data Analysis

The ocular refraction and pupillary diameter data for both eyes were exported to Microsoft Excel. If the pupil diameter changed >2 mm/frame because of blinking, the data

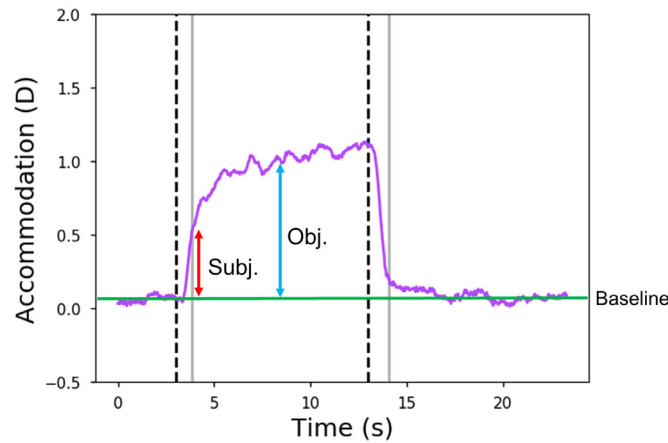


FIGURE 2. Calculation of objective and subjective accommodation and disaccommodation. The *purple line* indicates the representative accommodative response. The vertical *gray lines* indicate the accommodation and disaccommodation response times, the vertical *dashed lines* indicate the stimulus onset, and the *green line* indicates the baseline, which was calculated as median values between 0.5 and 2.5 seconds. The *light blue arrows* indicate the objective accommodation, which was defined as the difference between baseline and median values between 7 and 9 seconds (*black arrow*). The *red arrows* indicate subjective accommodation, which was defined as the difference between baseline and median values at the time of response. Subj, subjective; Obj, objective.

were excluded,¹⁸ and the missing values were replaced with linearly interpolated values calculated from an algorithm written with Python 3.6.5.

The subjective accommodation and disaccommodation response times were calculated as follows:

$$\begin{aligned} \text{Accommodation (disaccommodation) response time} \\ = (\text{time required to press button} - \text{reaction time}) \\ - \text{time when target changed} \end{aligned}$$

where the time for when the target changed was 3 seconds for accommodation and 13 seconds for disaccommodation.

The SE refractive values and pupillary diameter of the dominant eye were collected during 23-second measurements, and the average of the five trials was calculated for each subject. The median baseline SE refractive values and median pupillary diameters were calculated between 0.5 second and 2.5 seconds. The subjective amplitude of accommodation was defined as the difference in refractive values between baseline and the accommodation response time (Fig. 2). The objective amplitude of accommodation was calculated as the difference in refractive values between baseline and median refractive values during the 7- to 9-second interval.

The objective amplitude of pupil constriction was calculated as the difference between baseline and median values of accommodation between 7 and 9 seconds. The subjective amplitude of pupil constriction was defined as the difference between baseline and pupillary diameter at the time of the accommodation response time. The mean accommodative velocities and pupil constriction speeds were calculated from the mean differential values before and after 0.5 second according to the accommodation response time (Fig. 3a). Further, the onset of accommodation and pupil constriction were calculated from the intersection between baselines and slopes that were calculated from the accommodative velocities and pupil constriction speed (Fig. 3b). The latency of accommodation and pupil constriction was calculated as follows:

$$\begin{aligned} \text{Latency} = \text{onset time of accommodation (pupil constriction)} \\ - 3.0 (\text{stimulus onset time}) \end{aligned}$$

The latencies of accommodation and pupil constriction were calculated from the intersection of the baseline and slope that were calculated from the accommodative velocities and pupil constriction speed (Fig. 3b).

Statistical Analysis

The paired *t*-test was used to evaluate the significance of differences between the variables, including the following:

1. Response times of accommodation and disaccommodation
2. Subjective and objective accommodation
3. Pupillary diameter and each response
4. Mean accommodative velocity and pupil constriction speed
5. Latencies of accommodation and pupil constriction

Simple linear regression analysis was used to evaluate the relationship between the variables as follows:

1. Subjective amplitude of accommodation and the mean accommodative velocity during the 0.5 second preceding the accommodation response time
2. Objective amplitude of accommodation and the mean accommodative velocity during the 0.5 second preceding the accommodation response time
3. Latencies of accommodation and pupil constriction
4. Latency of accommodation and subject's age
5. Latency of pupil constriction and subject's age

SPSS Statistics 26 (IBM Corp., Armonk, NY, USA) was used to determine the significance of the differences, and $P < 0.05$ was considered to be statistically significant.

RESULTS

Demographics of Subjects

The mean SE values of the right and left eyes were -2.20 ± 2.75 D and -2.02 ± 2.59 D, respectively. Best-corrected visual acuity was equal to or superior to 0.0 logMAR (minimum angle of resolution) in all subjects.

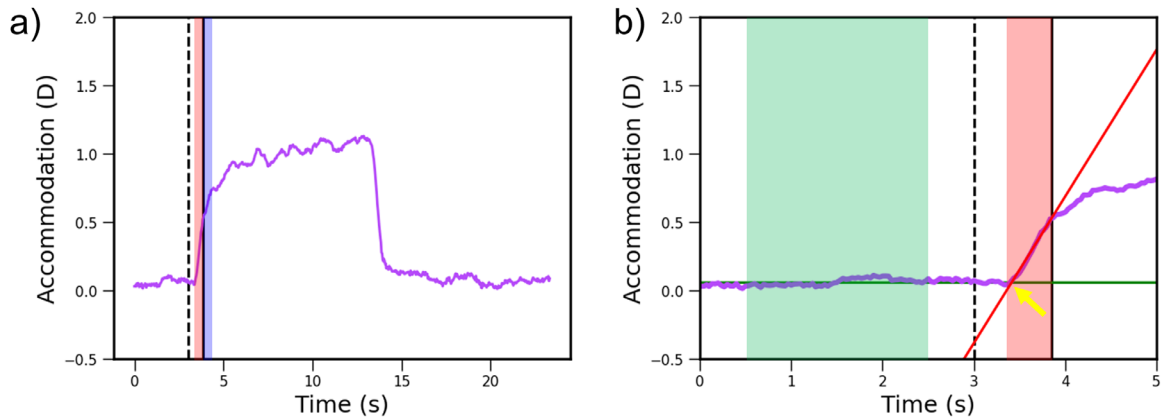


FIGURE 3. (a) Range of mean accommodative velocities before and after response times in the accommodation phase and calculated latencies. The purple line indicates a representative accommodative response, and the vertical solid and dashed black lines indicate the accommodation response time and stimulus onset, respectively. The red and blue bars indicate before and after 0.5 second, according to the accommodation response time. The mean accommodative velocities and pupil constriction speeds were calculated using the mean differential values before and after 0.5 second, according to the accommodation response time. (b) Expansion of the interval in a from 0.0 to 5.0 seconds. The red line indicates a linear approximation calculated using the least-squares method before 0.5 second, according to the accommodation response time (red bar). The green line indicates the baseline calculated using median values between 0.5 and 2.5 seconds (green bar). The yellow arrow indicates the onset of accommodation, defined as the intersection of the slope (red line) and baseline (green line). Latency = onset time - 3.0.

TABLE. Summary of Subjects' Reaction Times and Accommodative Parameters, Mean ± SD

Reaction Time (s)	Time Required to Press Button (s)	Response Time (s) [*]		Accommodative Amplitude (D) [*]	
		Accommodation	Disaccommodation	Objective	Subjective
0.32 ± 0.08	1.47 ± 0.56	1.14 ± 0.56	1.48 ± 0.79	0.97 ± 0.32	0.62 ± 0.43

^{*} P < 0.001.

Among the 34 participants, right-eye ocular dominance was observed in 16 and left-eye ocular dominance in 18. Using the dominate eye, with the best distance correction in place, all subjects were able to focus at 40 cm.

The response time was significantly faster in the accommodation phase (1.14 ± 0.56 seconds) compared with the disaccommodation phase (1.48 ± 0.79 seconds; P = 0.003) (Table).

Objective Versus Subjective Amplitude of Accommodation

Figure 4 shows the individual and mean changes in accommodation. During the accommodation phase, the objective amplitude of accommodation (0.97 ± 0.32 D) was significantly greater than the subjective amplitude of accommodation that was corrected for the reaction time (0.62 ± 0.43

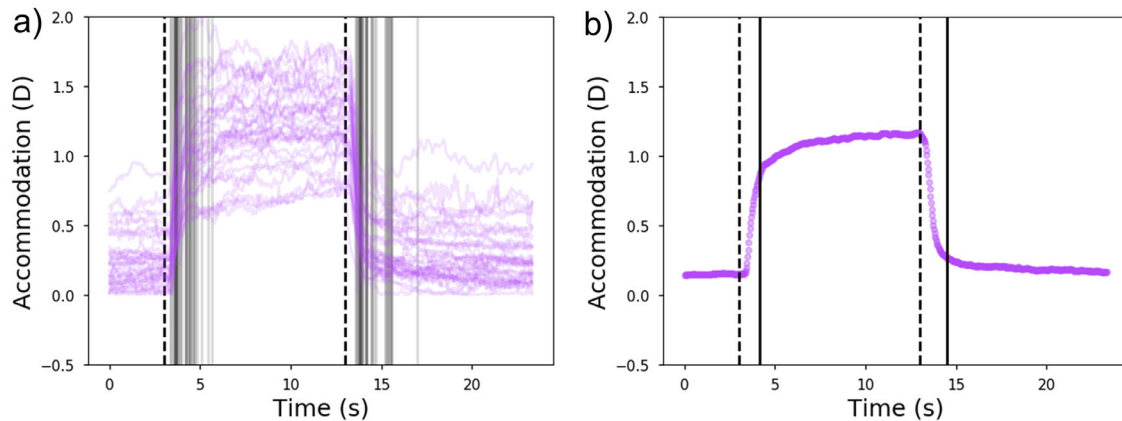


FIGURE 4. Individual and mean changes in accommodation. (a) The light purple lines indicate individual accommodative responses. The vertical gray lines indicate individual accommodation and disaccommodation response times, and the vertical dashed lines indicate stimulus onset. (b) The dark purple dots indicate mean accommodative response. The black solid and dashed lines indicate the mean accommodation and disaccommodation response time and stimulus onset, respectively.

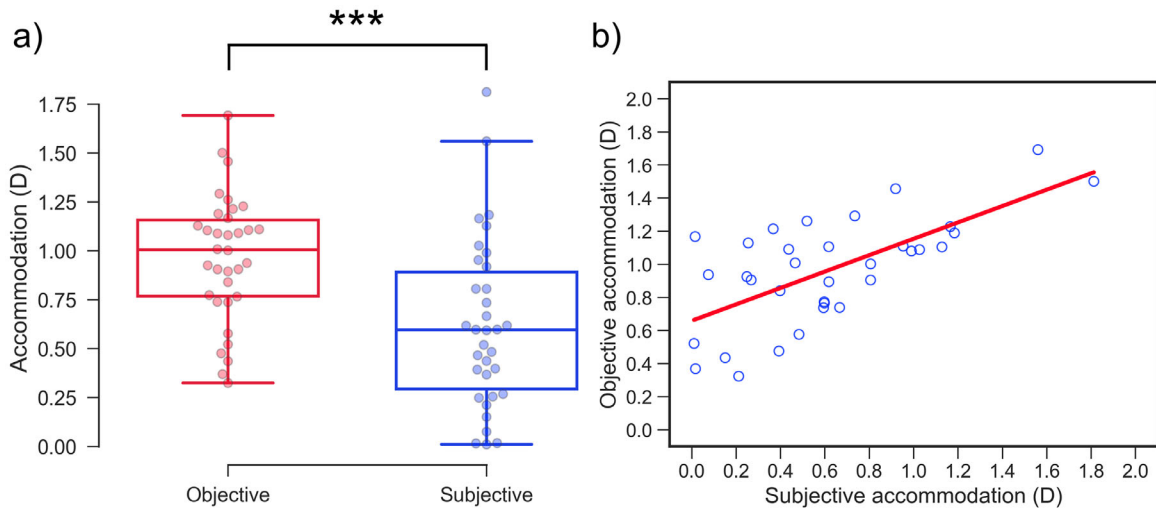


FIGURE 5. Difference in and relationship between objective and subjective accommodation. (a) The red and blue box plots with dots indicate objective and subjective accommodation, respectively. The objective accommodation was significantly greater than the subjective accommodation. *** $P < 0.001$, paired t -test. (b) The red line indicates regression. The objective accommodation significantly and positively correlated with subjective accommodation.

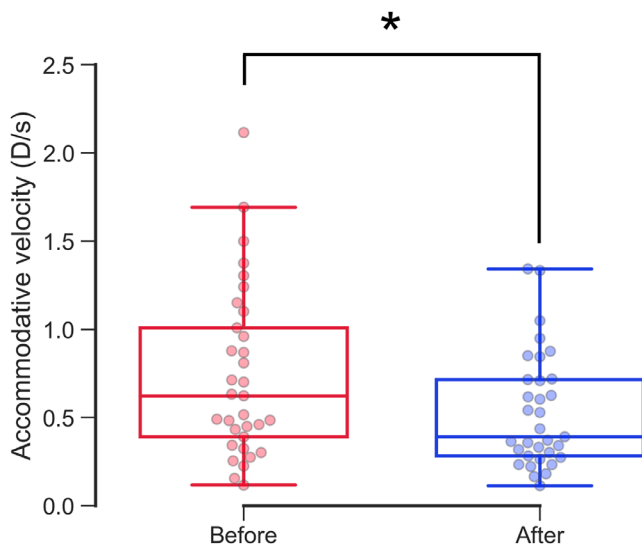


FIGURE 6. Difference in accommodative velocity between before and after visual recognition of the near target. The accommodative velocity was significantly slower for the “after the accommodation” response time than for the “before the accommodation” response time. * $P = 0.018$, paired t test.

D; $P < 0.001$) (Fig. 5a, Table). The objective amplitude of accommodation significantly and positively correlated with the subjective amplitude of accommodation ($R^2 = 0.44$, $P < 0.001$) (Fig. 5b).

The mean accommodative velocity was significantly faster during the 0.5 second preceding the accommodation response time (0.74 ± 0.48 D/s) than during the 0.5 second after the accommodation response time (0.52 ± 0.32 D/s; $P = 0.018$) (Fig. 6). The mean accommodative velocity during the 0.5 second preceding the accommodation response time was significantly and positively correlated with the subjective ($R^2 = 0.540$, $P < 0.001$) and objective ($R^2 = 0.144$, $P = 0.027$) amplitudes of accommodation (Fig. 7).

Pupil Changes

Figure 8 shows the individual and mean changes in pupillary diameter, which did not differ significantly between the two states (objective 5.63 ± 1.11 mm vs. subjective 5.74 ± 1.18 mm; $P = 0.22$). The pupillary diameters measured during objective and subjective accommodation significantly and positively correlated with each other ($R^2 = 0.889$, $P < 0.001$). The pupillary constriction speed was not significantly different before (0.64 ± 0.57 mm/s) or after (0.74 ± 1.06 mm/s) the accommodation response time ($P = 0.60$).

Pupillary constriction time (0.57 ± 0.40 second) was significantly slower than accommodation response time (0.33 ± 0.14 second; $P = 0.001$) (Fig. 9a). When one outlier was removed, there was no significant correlation between pupillary constriction and the accommodative response ($R^2 = 0.021$, $P = 0.42$) (Fig. 9b). The latencies of accommodation ($R^2 = 0.005$, $P = 0.69$) and pupil constriction ($R^2 = 0.059$, $P = 0.167$) did not significantly correlate with a subject’s age.

DISCUSSION

In this study, we evaluated the consistency of monocular objective and subjective accommodation using step stimulation from 0.20 D to 2.0 D in pre-presbyopes. We found that the subjective amplitude of accommodation was significantly less than the objective amplitude of accommodation (Figs. 4, 5). The accommodative velocity (D/s) was calculated by dividing the accommodative amplitude before and after 0.5 second of response time, which is the time the subject pressed the button. Accommodative velocity was significantly faster before than after the accommodation response time (Figs. 3, 6). These findings suggest that the human eye, under the monocular condition, first rapidly focuses on the near target and then after visual recognition slowly and accurately adjusts to focus sharply on the near target.

Previous studies that investigated the amplitudes, velocities, and latencies between subjective and objective

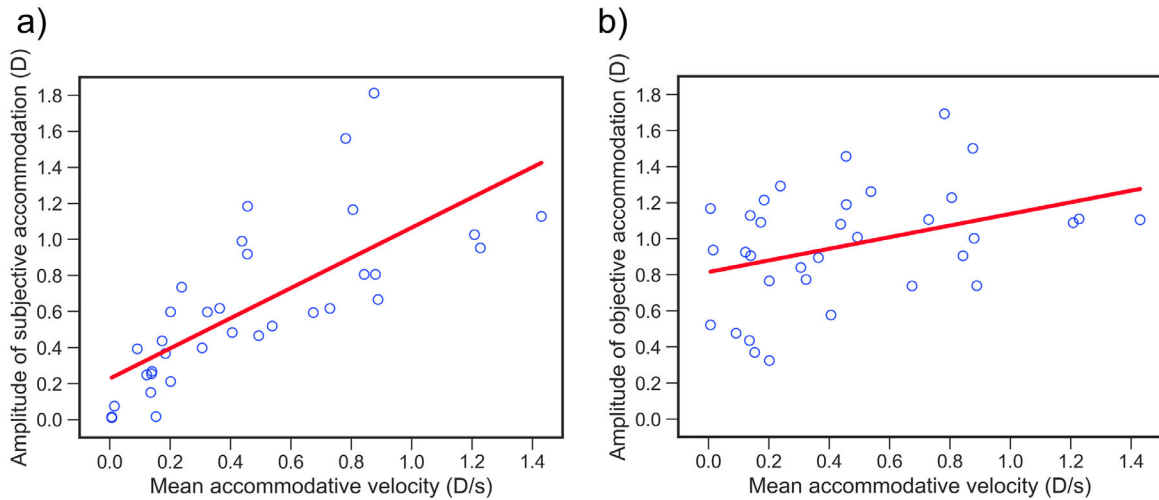


FIGURE 7. Relationships between mean accommodative velocity and amplitudes of subjective (a) and objective (b) accommodation velocities. The *red lines* represent the regression lines of a and b, respectively. The mean accommodative velocity during the 0.5 second before the accommodation response time was significantly and positively correlated with the amplitudes of both subjective and objective accommodation.

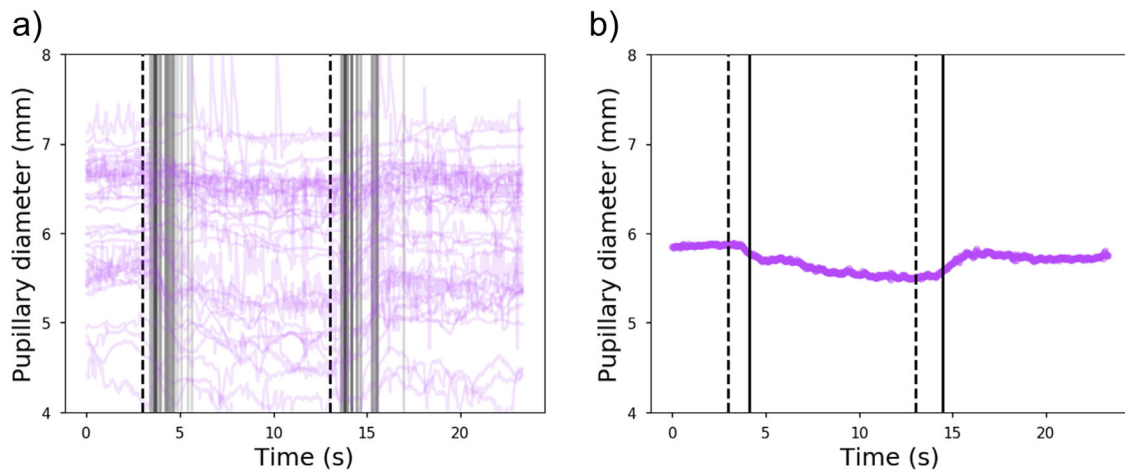


FIGURE 8. Individual and mean changes in pupillary diameters. (a) The *light purple lines* indicate individual pupillary diameters, the vertical *gray lines* indicate individual accommodation and disaccommodation response times, and the vertical *dashed lines* indicate stimulus onset. (b) The *dark purple dots* indicate mean pupillary diameter. The *black solid and dashed lines* indicate the mean accommodation and disaccommodation response time and stimulus onset, respectively.

accommodations have found that the subjective amplitude of accommodation was greater than the objective amplitude of accommodation.^{19,20} In contrast, in the present study, the subjective amplitude of accommodation was significantly less than the objective amplitude of accommodation. We attribute this discrepancy to the accommodative stimuli that differed between the present and previous studies. For example, in this study, we evaluated the amplitude of accommodation under the monocular condition using step stimulation between 0.20 D and 2.0 D in pre-presbyopic individuals with an estimated subjective accommodation of ≥ 2.5 D. In contrast, previous studies evaluated the maximum amplitudes of the subjective and objective accommodations.

The relationship between maximum velocity and maximum amplitude of accommodation (main sequence) is an indicator used to evaluate voluntary accommodation.^{21,22}

Although the maximum values of velocity and amplitude were not used in the present study, the mean accommodative velocity during the 0.5 second preceding the accommodation response time significantly and positively correlated with the subjective and objective amplitudes of accommodation (Fig. 7). These findings suggest that the relationship between velocity and amplitude of accommodation evaluates the objective accommodative response, as well as subjective accommodation.

The latency of accommodation is an indicator used to evaluate presbyopia.²² The latency reported here did not significantly or positively correlate with a subject's age. This finding suggests that these subjects were pre-presbyopic. The latency of accommodation in the present study was 0.33 ± 0.14 second using the BWFA with a sampling rate of 30 Hz. This finding supports the study of Mordt and

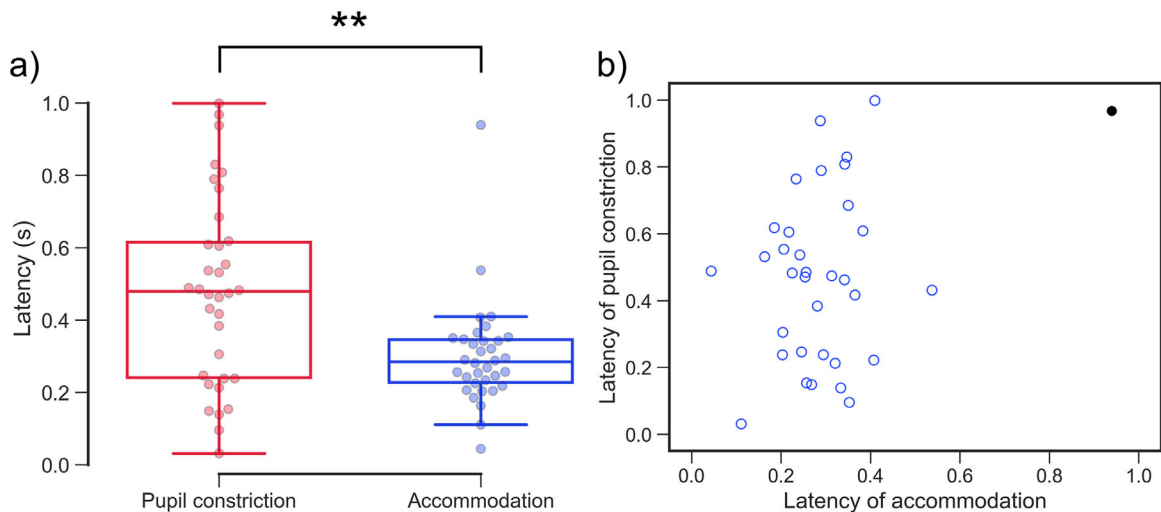


FIGURE 9. Differences and relationships associated with the latencies of pupil constriction and accommodation. (a) The red and blue box plots indicate latencies of pupil constriction and accommodation, respectively. The latency of pupil constriction was significantly longer compared with that of accommodation. $**P = 0.001$, paired t -test. (b) Without the outlier data, shown by the black dot, the latency of pupil constriction was not significantly correlated with that of accommodation ($R^2 = 0.021$; $P = 0.42$).

Ciuffreda,²² who found that the latency of accommodation ranged from 325 ± 35 ms to 530 ms between young adults and presbyopic individuals, which was determined using an infrared optometer with a 5-Hz sampling rate.

Although the pupil constricts with accommodation, in the present study pupillary diameter did not significantly change during objective or subjective accommodation. This may be explained by our evaluation of a small accommodative stimulus (1.8 D). Radhakrishnan and Charman²³ studied the response of the pupil to accommodative stimuli in healthy individuals 17 to 56 years of age and found that pupil constriction occurred infrequently with an accommodative stimulus of 2.0 D. Consistent with prior studies,²⁴ the latency of pupil constriction was significantly greater than that of accommodation (Fig. 8a).

This study was unique because the subject's reaction time was measured independently and repeatedly prior to evaluating the accommodative response. The subject's mean reaction time was subtracted from the time required to press the button, permitting a more accurate assessment of the accommodative response. Using this paradigm, the response time was shorter and the velocity was faster for accommodation than for disaccommodation. This finding is consistent with that of Labhishetty et al.,²⁵ who determined the accommodative response time only after the velocity exceeded 0.5 D/s and continued for the next 100 ms.²⁶ In studies that did not include these criteria or performed independent reaction time measurements for the assessment of accommodative response in subjects 20 to 50 years of age, the response for accommodation was essentially the same^{27,28} or slower⁴ than that for disaccommodation.

The subjective accommodation response time was faster in accommodation than in disaccommodation when those were adjusted by individual reaction time (Table). Sperandio et al.²⁹ and Cheng et al.³⁰ found that the reaction time did not change significantly based on target distance if the visual angles of the target sizes were equal. However, the present study found that ocular refraction at the response time in disaccommodation was close to baseline compared

with that in accommodation (Fig. 4b). Beers and Van Der Heijde³¹ found that the time constant of accommodation was larger than that of disaccommodation. The inconsistencies between the present and previous findings may be explained by visual attention and muscular force. Reaction time is consistently slower in the monocular condition than in the binocular condition.³² Arnott and Shedden³³ used a random dot stereogram of reaction times for recognizing two objects between near and distant. The reaction times were faster from distant to near than from near to distant. Further, they showed that the reaction times required to switch the target from distant to near did not change significantly if the target was at a constant distance, such as in the present task.

Generally, when a muscular force is applied, the response is faster in the constriction phase than in the relaxation phase. Bremner³⁴ determined the dynamics of the pupillary response using a light stimulus and found that the pupil moved faster when the light was on (active force) than when the light was off (passive force). If the center of the lens becomes preferentially myopic because of increased zonular tension during adjustment, the Schachar theory would be applicable.^{35–38}

The present study has some limitations. Most predominantly, we measured and evaluated changes in accommodation and pupillary diameter under the monocular condition. Considering the monocular condition would eliminate vergence accommodation; however, we live with both eyes open. The near reaction involves the three components of convergence, accommodation, and miosis. According to Heron et al.,³⁹ convergence functions the fastest among them; therefore, we plan to investigate accommodative responses under the binocular condition in future work.

CONCLUSIONS

Subjective accommodation was significantly lower than objective accommodation in this research, and the

accommodative velocity was found to decrease significantly after visual recognition. These findings suggest that the human eye, under the monocular condition, adjusts to the focus plane quickly to archive the nearby object clearly, whereas the focus plane thereafter is slowly and accurately adjusted to the visual target after visual recognition.

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SUPPLEMENTARY MATERIAL

SUPPLEMENTARY VIDEO S1. Introduction for BWFA. BWFA can measure and record binocular eye movement, wavefront aberrations, and pupil size simultaneously, at a sampling rate of 30 Hz. BWFA, open-view Shack -Hartmann wavefront aberrometer.

SUPPLEMENTARY VIDEO S2. Step stimulation. The accommodative stimulation was set at 50 cm. The distant target was displayed for 3 seconds; the target distance was subsequently changed from distant to near for 10 seconds and then from near to distant for 10 seconds.

SUPPLEMENTARY VIDEO S3. Measuring reaction time. An algorithm written with Python 3.6.5 was used to record the reaction times. All subjects were asked to fixate the center of the cross target. Then, pressing the button immediately after the fixation target changed from cross to asterisk. All subjects performed 20 reaction time trials under the best correction at distant.