ORIGINAL INVESTIGATION

Stimulus Unpredictability in Time, Magnitude, and Direction on Accommodation

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SIGNIFICANCE: The effect of predictability in changes of time, magnitude, and direction of the accommodation demand on the accommodation response latency and its magnitude are insignificant, which suggests that repetitive accommodative tasks such as the clinical accommodative facility test may not be influenced by potential anticipation effects.

PURPOSE: The purpose of this study was to investigate the effect of stimulus' time, magnitude, and direction predictability, as well as their interactions, on accommodation latency and response magnitude.

METHODS: Monocular accommodative response and latency were measured in 12 young subjects for nine different conditions where the stimulus accommodative demand changed several times in a steplike fashion for a period of 120 seconds. Each change in accommodative demand could have different time duration (i.e., 1, 2, or 3 seconds), magnitude (1, 2, or 3 diopters), and/or direction (i.e., accommodation or disaccommodation). All conditions were created permuting the factors of time, magnitude, and direction with two levels each: random and not random. The baseline condition was a step signal from 0 to 2 diopters persisting for 2 seconds in both accommodative demands. After each condition, subjects were asked to provide a score from 1 to 5 in their perceived predictability.

RESULTS: Friedman test conducted on the perceived predictability of each condition resulted in statistically significant differences between the nine conditions ($\chi^2 = 56.57$, $P < .01$). However, repeated-measures analysis of variance applied to latency and accommodative response magnitude did not show significant differences ($P > .05$). In addition, no correlation was found between the perceived predictability scores and both latency and accommodative response magnitudes between the most predictable and the most unpredictable conditions.

CONCLUSIONS: Subjects were able to perceptually notice whether the stimulus was predictable or not, although our results indicate no significant effect of stimuli predictability on either the accommodation latency or its magnitude.

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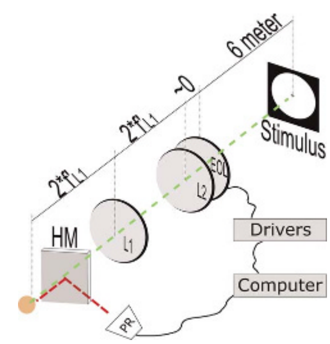

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The accommodative system can respond reasonably quickly and accurately to a variety of dynamically changing stimuli using either stimuli modulated in step, sinusoidal, or ramp changes in defocus or near vision demands.[1–4] A square wave–modulated or a sinusoidally modulated stimulus may be predictable to observers if the accommodative demand is changed after a repetitive and well-defined pattern in magnitude (the dioptric change between two accommodative states), direction (either accommodation or disaccommodation), and time (the period that the fixation target remains in each accommodative demand).

More than 50 years ago, some authors[5–7] mentioned the possibility that the human accommodative system is able to anticipate future accommodation stimulus changes; that is, there might exist a prediction operator that reduces response latency in predictable compared with random, accommodative stimulus. This concept was further investigated by Phillips et al.[2] in 1972. They measured monocular accommodative responses to square wave–modulated stimuli for four subjects and found a mean reduction in response latency of 204 milliseconds when using a square wave stimulus instead of a nonpredictable stimulus. The mean reduction in response latency was highly skewed; when the mode difference was computed, the reduction was only 49 milliseconds. In the following 2 years, Krishnan et al.[1] and van der Wildt et al.[3] investigated the presence of the prediction operator in repeatable sinusoidally modulated stimuli and concluded that the effect of prediction is small but not negligible. Interestingly, one subject studied by van der Wildt et al.[3] was not able to follow the accommodation stimulus despite its predictability.

It is important to note that all these studies were each limited in sample size and difficult to reproduce because of the lack of information on the participants' age, refractive error, or the explicit task instructions. As shown in previous studies, the accommodative response and some parameters of its dynamics (e.g., latency) are significantly affected by age,[8,9] refractive error,[10,11] and the instructions given to participants.[12] When these factors are not controlled, they could mask or bias the findings. In addition, most of the subjects in these studies were presumably the authors themselves, with consequent biases associated with the knowledge of the nature of the study and extensive training in similar studies. After the aforementioned studies carried out approximately 40 years ago, little has been investigated in relation to a possible prediction operator in accommodation.

Most subsequent accommodation dynamic studies have used predictable stimuli, either sinusoidal or square wave, and have assumed the presence of anticipation effects.[8,10,13] A few studies considered random stimuli either in time[9,14,15] or magnitude[16] to avoid the possible effect of prediction. To our knowledge, there is a question related to a possible prediction operator in accommodation that is not yet answered: Is prediction affected by the interactions between the factors that define a predictable stimulus (i.e., time, magnitude, and direction)?

The effect of each of these factors, time, magnitude, and direction, in isolation has not been studied previously. The answer to this question would provide a deeper understanding, at a fundamental level, of the role that the prediction operator has in the models of oculomotor control.[17] Moreover, the investigation of the effect of time, magnitude, and direction in accommodation responses would also provide insights into the effect that anticipation has in clinical tests such as accommodative facility.[10,18] In this test, predictable stimuli are used to evaluate visual fatigue to focus changes.[19] The purpose of this study is therefore to investigate the effect of stimulus' predictability in time, magnitude, and direction, as well as their interactions, on reflex and voluntary accommodation latency and response magnitude.

METHODS

Subjects

The research was performed according to institutionally approved human subject protocols with fully informed consent provided by each subject, and it followed the tenets of the Declaration of Helsinki. Criteria for inclusion were as follows: (1) best-corrected visual acuity of 0.00 logMAR (20/20 Snellen equivalent) or better in each eye; (2) between 21 and 28 years of age; (3) spherical equivalent error in each eye, as measured with subjective refraction, between –6.50 and +0.50 diopters; (4) amplitude of accommodation greater than the value given by the Hofstetter average formula for accommodation[20] (amplitude = 15 – 0.25 * age); (5) no strabismus, amblyopia, binocular, or accommodative anomalies; and (6) no history of any ocular disease, surgery, and/or pharmacological treatment that may have affected vision at the time of the study. Subjects with myopia wore their own disposable soft contact lenses during the study. All contact lens prescriptions were within ±0.50 diopter of the subject's best-corrected spherical equivalent, determined by subjective refraction, as explained hereinafter. A total of 12 subjects (with some experience in accommodation studies) who met the inclusion criteria were tested and included in the analyses.

Instrumentation and Stimuli

A binocular open-field autorefractor, PowerRef II (Plusoptix Inc., Atlanta, GA), was used to measure accommodation responses. This autorefractor is based on the principle of dynamic infrared retinoscopy, and it measures spherical equivalent, pupil size, and gaze position at a sampling frequency of 25 Hz.[21,22] The PowerRef II refractor was calibrated for each subject. In short, six different trial lenses (from +4.00 to –1.00 diopters, in 1-diopter steps) were randomly placed in a trial frame fitted to each subject. For each trial lens, subjects monocularly fixated a far-distance stimulus during a period of 4 seconds, whereas the contralateral eye was eye patched. During this period, objective refraction was obtained with the PowerRef II in the open eye. From each recording, the mean refraction was computed and compared with that expected from the trial lenses. A linear regression was obtained comparing the six measured refractions with the expected refraction given by each trial lens. The slope and intercept of the linear fitting obtained from this calibration were used as a correction factor for each subject's measurements in all experimental conditions. The linear correlation coefficient values obtained in all subjects were greater than 0.75. Although this calibration procedure is not optimal because subjects are likely to accommodate over the top of the –1-diopter lens and also for high blur (+4 diopters), the same calibration is used for all study conditions.

To align the PowerRef with the subjects' eye while viewing the target, a 50-mm square infrared hot mirror (transmits visible light and reflects infrared light) was placed at 40 mm from the subjects' pupil plane. Subjects looked at the accommodative stimulus through an optical system that comprised three lenses (Fig. 1A). The first lens (L1; diameter of 50 mm, focal length of 100 mm) was placed 200 mm from the subject's pupil (twice f_{L1}). In this way, a pupil conjugate plane was created 200 mm away from the lens, without magnification. The active module that performed the accommodation stimulation was placed in that plane and was composed of an electro-optical lens[23] (EL-16-40-TC; Optotune Switzerland AG, Dietikon, Switzerland) and a second lens (ophthalmic type) attached to it (L2; diameter of 25 mm, power of +3 diopters). The electro-optical lens had a spherical power range from –10 to +10 diopters, with a reproducibility of ±0.05 diopter and a settling time of 25 milliseconds (according to the manufacturer's specifications).

The target was placed at 6 m from the electro-optical lens. This design ensured both the linearity and the 1:1 relationship between the power applied by the electro-optical lens and the accommodation stimulus to the subject, as well as a constant stimulus size despite changes in accommodative demand. The lens L2 shifted 3 diopters, the working range of the electro-optical lens, to avoid its operation limits (far vision corresponds to an electro-optical lens power of +7 diopters instead of +10 diopters), thus guaranteeing its best performance. The overall system can accurately measure an accommodative range up to 10.00 diopters. The field of view was constant with a diameter of 14.25°. The response time for each step change of accommodative demand was approximately 40 milliseconds (response time of the electronics + settling time of the electro-optical lens). The electro-optical lens power was controlled by a driver connected to a computer by means of a software application specifically developed for this study that synchronized the accommodative demand changes with the PowerRef II. In each change of accommodative demand, the electro-optical lens power was set before a pulse was sent to the PowerRef II. To avoid possible thermal drifts on the electro-optical lens response, the lens was heated to 28°C before the beginning of the sessions and kept of that temperature throughout the procedures. Moreover, the electro-optical lens response at that temperature was calibrated before its integration into the system by means of a digital lensometer CL-300 (Topcon Corp., Tokyo, Japan), including the calibration curve in the software application.

The accommodative target used for all conditions was a 2° high-contrast black Maltese cross on a white uniform background (Fig. 1B), with average luminances of 3.7 and 56.2 cd/m^2 for the black and white regions, respectively. Although this stimulus does not have peripheral depth cues, which could have improved the accommodative response,[24,25] it is the most frequently used stimulus for accommodation studies owing to its wide frequency spectrum,[26] and it is easily reproducible. The use of this stimulus allows for direct comparisons of our results with previous studies of dynamic accommodation.[9,27,28]

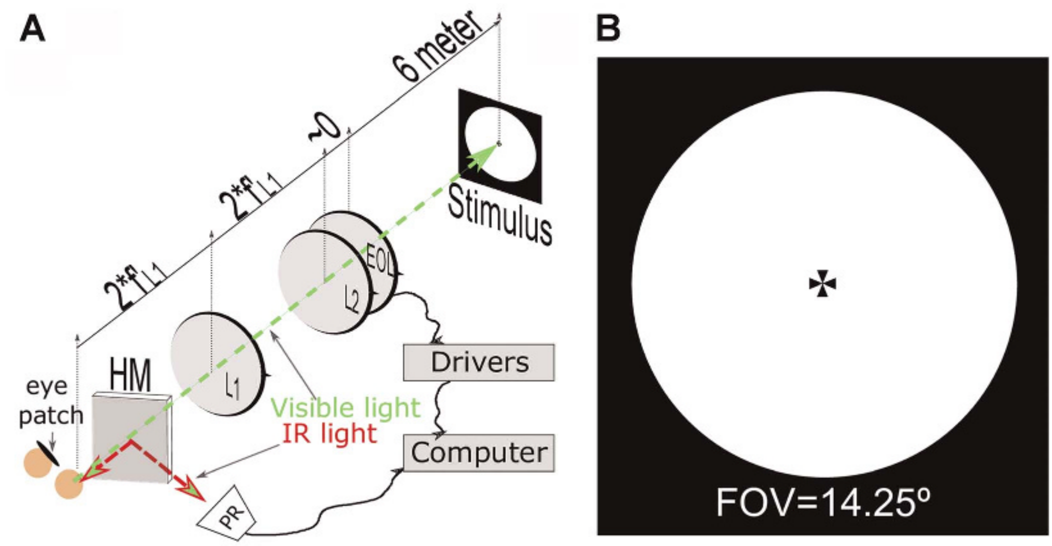

FIGURE 1. (A) Schematic view of the setup. (B) Accommodative stimulus used in the experiment. EOL = electro-optical lens; *f*′ = focal length; HM = hot mirror; L1 = first lens with a diameter of 50 mm and a focal length of 100 mm; L2 = second lens with a diameter of 25 mm and a power of +3 diopters; PR = PowerRef II.

Examination Protocol

Monocular subjective refraction with end point criterion of maximum plus power that provides best visual acuity followed by binocular balance was performed to determine each subject's best optical correction. The dominant sensory eye (resistance to +1.50-diopter blur)[29] was chosen for the measurements, whereas the fellow eye was occluded with an eye patch. Subjects' pupil size was not controlled or artificially limited during the experiment, and monocular subjective amplitude of accommodation was evaluated by averaging the values of two push-up and two push-down trials.[30]

Monocular accommodative responses were measured for nine randomly presented conditions where the accommodative demand changed several times in a steplike fashion for a total time of 120 seconds. Subjects were instructed to clear the target naturally, and they were not asked to comment on the clarity of the target under any of the experimental conditions. Each change in accommodative demand (i.e., trial) could have different time duration (1, 2, or 3 seconds), magnitude (1, 2, or 3 diopters), and/or direction (accommodation or disaccommodation). All conditions were created, permuting the factors of time, magnitude, and direction in a random or not random fashion. The default values for not random factors of time and magnitude were 2 seconds and 2 diopters, respectively. For direction, the default value was accommodation until the demand reached 4 diopters; at that moment, the direction was reversed to disaccommodation until it reached 0-diopter accommodation demand. Fig. 2 shows the nine testing conditions used in the study.

Notice that when time, magnitude, and direction were not random, the input signal followed a well-defined step function going from 0 to 4 diopters and from 4 to 0 diopter in steps of 2 diopters and staying a period of 2 seconds in each accommodative demand (Fig. 2, panel 2). This condition with three accommodative states was considered a baseline reference for the analyses. This baseline condition was different from the signals used in other dynamic accommodation studies, in which only two accommodative states were considered.[10,13,22,31] To extrapolate our results to other dynamic accommodation studies such as those cited in Introduction, we included one extra baseline condition: a square wave signal going from 0 to 2 diopters in steps of 2 diopters and staying a period of 2 seconds in both accommodative demands (Fig. 2, panel 1). This condition will constitute the most predictable condition in this study.

After each trial, subjects were asked to rank on a 5-point scale their subjective perception of predictability for that condition, with level "1" indicating that the accommodation level was fully predictable and level "5" indicating that it was totally unpredictable. The examiner recorded these subjective responses. All subjects were naive to the purpose of the study, but they were trained at the beginning on what constitutes a predictable condition. Subjects were trained using the far-distance accommodative facility test, consisting on repeatedly changing the accommodative demand between 0 and 2 diopters during a period of 60 seconds. For this training, the fixation target was at 6-m distance, and the 2-diopter accommodative demand was lens induced with an accommodation flipper held by the operator that had an ophthalmic lens of −2.00 diopters. Subjects were informed that this would be a fully predictable condition (i.e., score value of 1).

All conditions were measured once in one session that took approximately 30 minutes, including breaks. Subjects were allowed to take breaks as needed, although there was no systematic method to provide rests during the measurements. Randomization of configurations was rigorously applied to minimize potential learning or fatigue biases.

Data Analyses

Data were processed and analyzed using MATLAB R2015b (MathWorks, Inc., Natick, MA). Because the dynamics of accommodation and disaccommodation are dependent on amplitude,[32] the main analysis considered the accommodative changes ("transitions") from 0 to 2 diopters (accommodation) and from 2 to 0 diopter

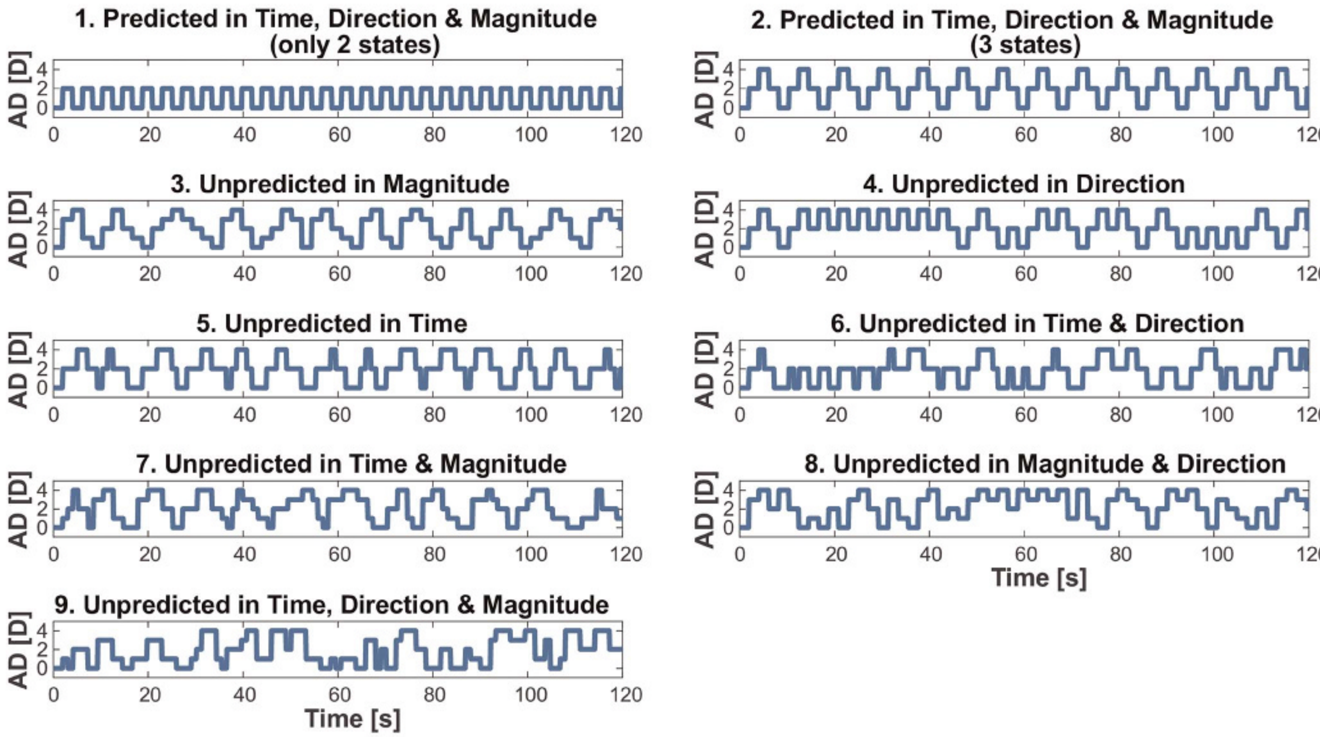

FIGURE 2. Examples of each accommodation step change (nine conditions) tested in the experiment. The simplest and most predictable condition (baseline) is plot 1. The most unpredictable condition is plot 9 (totally unpredictable in time, direction, and magnitude). AD = accommodative demand.

(disaccommodation) only, although for comparison purposes, a secondary analysis also included the transitions 2/4 diopters. In each transition, both accommodative latency and response magnitude were computed. Subsequently, a repeated-measures analysis of variance was computed for both latency and accommodative response magnitude with two within-subjects' factors: condition (with nine levels) and direction of accommodation (with two levels).

Latency was defined as the period (in seconds) between the start of the accommodative stimulus change and the start of the accommodative response by the subject, computed as described by Kasthurirangan et al.[32] To determine the start of the accommodative response, a custom algorithm was created to search for three consecutive increasing data values, followed by four consecutive data values in which no two consecutive decreases occurred; the first data point in this sequence was recorded as the start of the response. The inverse algorithm was used to determine the start of the disaccommodative response. It should be noted that the algorithm used in this study considers only latencies greater than or equal to zero. To explore the latency algorithm further, the algorithm was modified in such a way that negative latencies could be detected up to −560 milliseconds in steps of 40 milliseconds. The proportion of times where we found latencies <40 milliseconds for both the most predictable (condition 1) and the most unpredictable (condition 9) conditions was very similar (Appendix Fig. A1, available at http://links.lww.com/OPX/A401), which suggests that the latency algorithm affects both the most predictable and unpredictable conditions in the same way. However, other authors have used a velocity-criterion algorithm to compute latency, which may be more accurate and more indicated when using procedures with higher sampling rates (e.g., 200 Hz).[14,27] The *accommodative response magnitude* at each accommodative transition was computed as the difference in diopters between the median response of the last four samples and the median response of the first four samples of the interval. Missing data points (e.g., due to blinks) were not interpolated, and only those accommodative transitions in which there were at least eight valid data points during the accommodative interval were included in the analysis. A valid data point was considered when pupil diameter was properly detected and a refraction measure was given by the PowerRef II.

The perceived predictability scores given by the participants for each condition were analyzed using Friedman tests and Wilcoxon tests with Bonferroni correction, to determine which pairwise comparisons were significant. Statistical power was determined using free open-source G*Power 3.0.10 (Universität Düsseldorf, Düsseldorf, Germany).[33] Data from a pilot study with four subjects were used to compute the required sample size for a statistical power of 0.8. Considering a significance of 0.05 and an analysis of variance model with nine repetitions, the required sample size was seven subjects.

RESULTS

Subjects had a mean age ± standard deviation of 25 ± 2 years, a mean monocular subjective amplitude of accommodation of 11 ± 2 diopters, and a mean subjective spherical equivalent of −1.45 ± 1.89 diopters.

Perceived Predictability Analysis

The Friedman test conducted on the perceived predictability of each condition resulted in statistically significant differences between the conditions (χ^2 = 56.57, P < .01). However, Bonferroni post hoc tests did not show statistically significant differences for any pairwise comparison (all P values were >.05/36, with 36 as the number of possible pairwise comparisons). Descriptive statistics of each condition are shown in Fig. 3.

Accommodative Latency Analysis

Repeated-measures analysis of variance applied to latency for the nine conditions tested (Fig. 4A) did not show significant effects for direction of accommodation (accommodation or disaccommodation; F = 3.15, P = .10), condition (F = 0.94, P = .49), or the interaction direction × condition (F = 1.20, P = .31). The median latency for each subject and condition is shown in Appendix Table A1, available at http://links.lww.com/OPX/A402.

The Spearman correlations (ρ, P value) between the perceived predictability scores and latency responses for the most predictable condition (condition 1) and the less predictable condition (condition 9) are shown in Figs. 5A, B, respectively, with the corresponding regression coefficients.

Analogously, the Spearman correlations between the latency responses obtained versus time are also shown in Figs. 6A, B, respectively, for the most predictable and less predictable conditions and for both accommodation and disaccommodation. In all regressions, the slope is less than 0.01, and the regression coefficients go from 0.02 in the worst case to 0.16 in the best case. None of the correlations are statistically significant (P > .05).

Accommodative Response Magnitude Analysis

Repeated-measures analysis of variance applied to accommodative response magnitude for the nine conditions tested (Fig. 4B) did not show significant effects for direction of accommodation (F = 0.37, P = .56), condition (F = 0.48, P = .75), or the interaction direction × condition (F = 1.39, P = .25). The median accommodative response for each subject and condition is shown in Appendix Table A2, available at http://links.lww.com/OPX/A403.

Analogously to latency analysis, the Spearman correlations and regression coefficients between the perceived predictability scores and accommodative response magnitudes for the most predictable condition (condition 1) and the less predictable condition (condition 9) are shown in Figs. 5C, D, respectively. The Spearman correlations between the accommodative response magnitudes and time of the most predictable condition and the less predictable condition are also shown in Figs. 6A, B, respectively.

Finally, to gain insight into whether the prediction operator in accommodation depends on its starting point, we compared the latency and accommodative response magnitude values obtained for two different starting points: transition in accommodative demand between 0 and 2 diopters and between 2 and 4 diopters. The results are shown in Fig. 7. Note that data points of this figure were exclusively obtained from condition 2, that is, a double-step wave–modulated stimulus that is predictable in time, direction, and magnitude.

DISCUSSION

Some authors[5–7] suggested that observers might be able to anticipate subsequent changes in accommodation demand. This idea was further tested by Krishnan et al.,[1] Phillips et al.,[2] and van der Wildt et al.[3] The conclusion from these studies is that, when using repeatable stimuli (e.g., sinusoids), accommodative latency can be reduced and the accommodative response accuracy can be enhanced. In this study, we investigated the effects of accommodation predictability factors such as time, magnitude, and direction of the accommodative change, as well as the interactions between these factors, on the accommodation response latency and magnitude.

Our results indicate no significant effect of stimuli predictability on either the accommodation latency or its magnitude when using two different types of analysis. No statistically significant differences were found when comparing the average latency and accommodative response magnitude across all conditions (Fig. 4). In addition, the individual data scatterplots shown in Fig. 6 did not reveal any systematic increase or decrease for both variables during the 120 seconds that lasted each condition. Based on previous studies and considering that there exists a prediction effect in certain ocular movements (i.e., saccades)[34] for repetitive stimuli, we initially expected that accommodation latency would be larger for unpredictable stimuli. However, no statistically significant effect was found for accommodative latency, at least no effect larger than

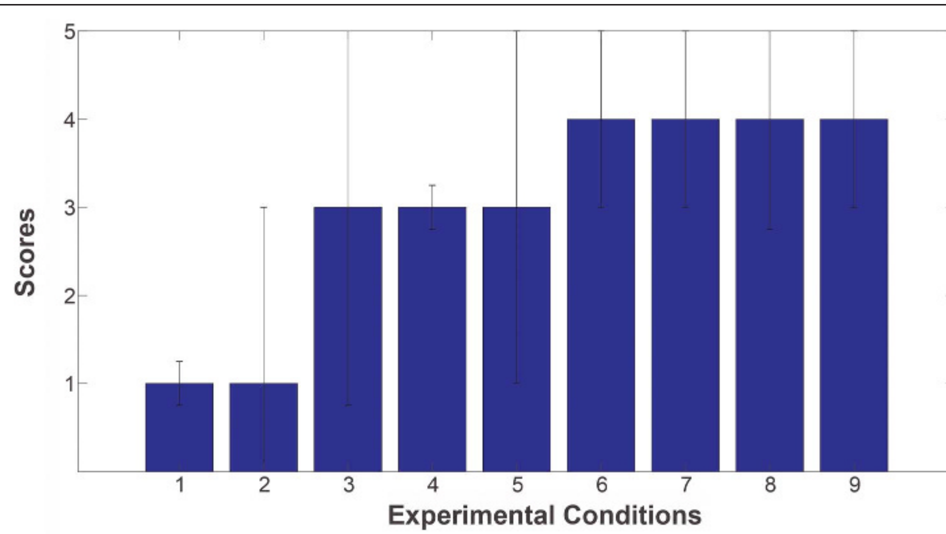

FIGURE 3. The median and interquartile range of the perceptual predictability scores given to each condition.

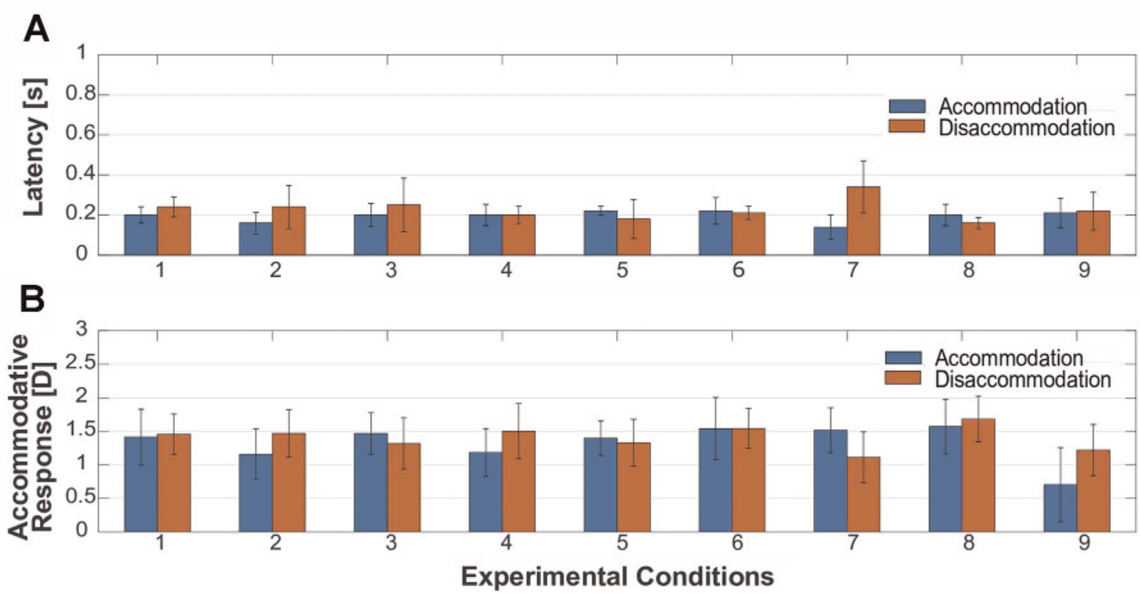

FIGURE 4. The median and interquartile range obtained for each testing condition and direction of accommodation for both variables: latency (A) and accommodative response magnitude (B). Data obtained from the transitions between 0 and 2 diopters of accommodative demand only.

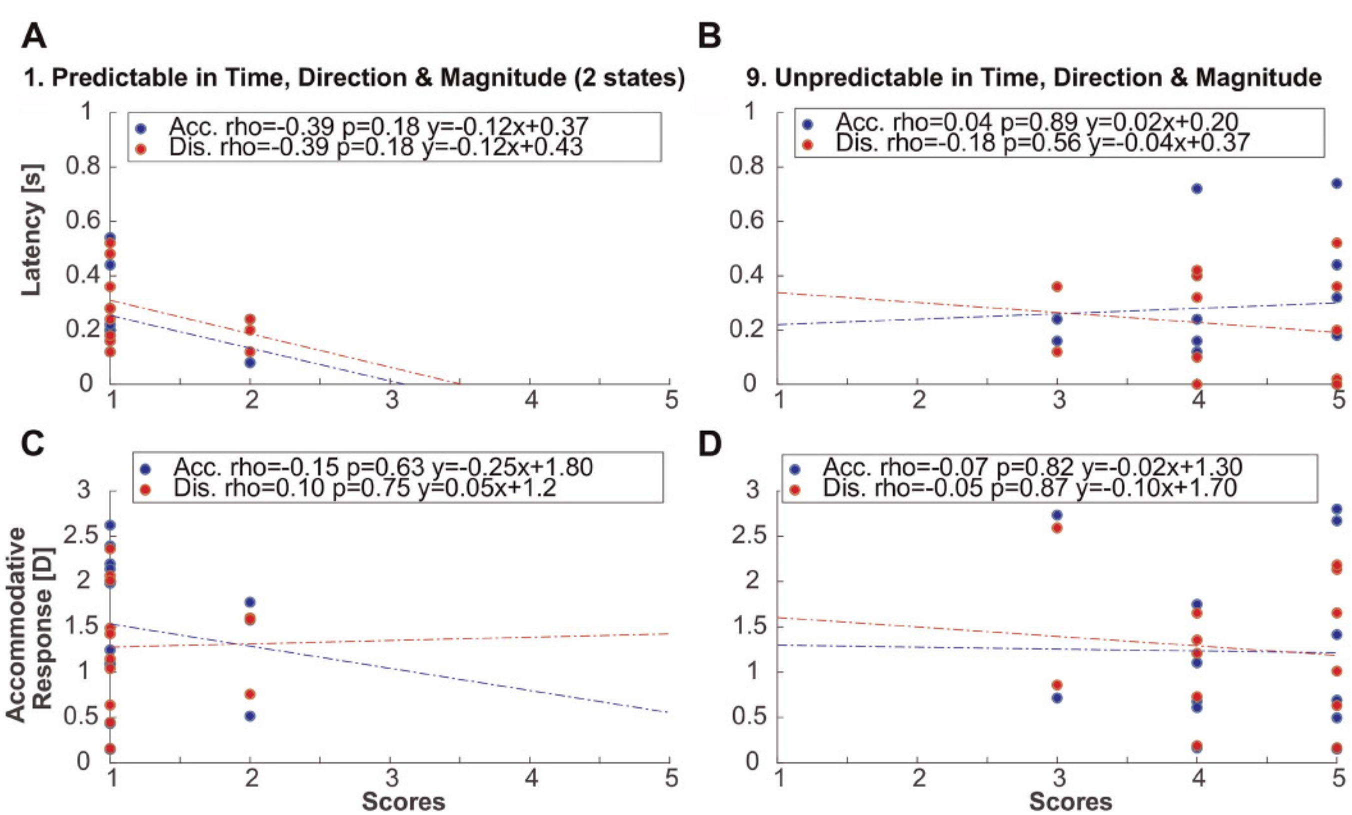

FIGURE 5. Scatterplots between (A to B) latency or (C to D) accommodative response magnitude and subjective predictability scores for conditions 1 (i.e., predictable in time, direction, and magnitude) and 9 (i.e., unpredictable in time, direction, and magnitude), and accommodation (Acc.; blue circles) and disaccommodation (Dis.; red circles). The Spearman correlation coefficient, the *P* value for each correlation, and the regression coefficients are shown in each plot's legend.

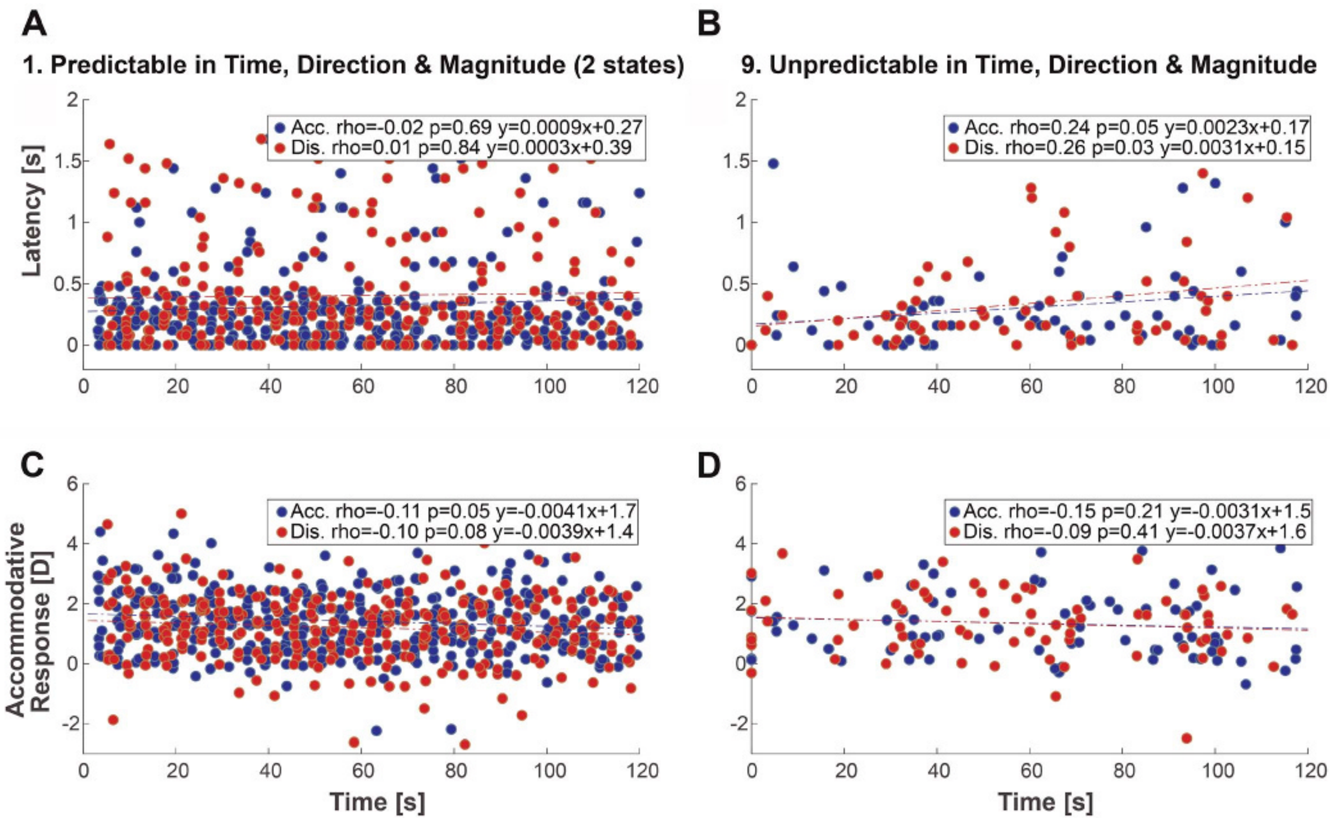

FIGURE 6. Scatterplots between (A to B) latency or (C to D) accommodative response magnitude and time for conditions 1 (i.e., predictable in time, direction, and magnitude) and 9 (i.e., unpredictable in time, direction, and magnitude), and accommodation (Acc.; blue circles) and disaccommodation (Dis.; red circles). The Spearman correlation coefficient, the *P* value for each correlation, and the regression coefficients are shown in each plot's legend.

the 40 milliseconds detectable by the PowerRef II autorefractor. The limited sampling rate of the device does not preclude the prediction operator to exist for values less than 40 milliseconds. To analyze how this limitation affected our results, the proportion of times where we found latencies of 0 milliseconds for both the most predictable (condition 1) and the most unpredictable (condition 9) conditions was computed. For condition 1, there were 14 and 17% of the cases for accommodation and disaccommodation, respectively. Analogously, for condition 9, 18 and 16% of the cases were found, respectively, for accommodation and disaccommodation. These results indicate that in both conditions in equal to or more than 82% of the cases latencies were larger than the sampling resolution of the instrument; thus, there is an uncertainty in 18% of the cases or less in which it is not exactly known if there was a prediction effect (of <40 milliseconds). As shown in Appendix Fig. A1 (available at http://links.lww.com/OPX/A401), these results can be affected by the way latency is obtained. Alternative algorithms to compute latency exist in the literature,[14,27] although it is not clear yet what is the most appropriate one.

A number of factors may account for the differences between our data and previous studies. Unsurprisingly, we found large intersubject standard deviations, which could, to some extent, explain the lack of statistical significance found in all analyses. However, the statistical power was greater than 0.8 for all response variables in this study, and it has been reported by Schaeffel et al.[21] and Heron et al.[35] that the dynamics of accommodative responses exhibit significant intersubject variability. Another possibility is that the prediction operator in accommodation depends on its starting point. Bharadwaj and Schor[14,36] comprehensively analyzed the dynamics of ocular accommodation and disaccommodation and reported that the peak velocity and peak acceleration of disaccommodation increased with the proximity of starting position. However, for a given starting position, these authors found accommodation magnitude responses to be invariant to the starting level. To gain insight into this question, Fig. 7 compares the latency and accommodative response magnitude values obtained for two different starting points. This figure shows that disaccommodation is more affected by the starting level than accommodation, which is consistent with the results obtained by Bharadwaj and Schor,[14,36] but overall, latency is not significantly affected by the starting level, and there is not a significant systematic bias in the accommodative response. These results indicate that changes in accommodation latency and response magnitude with predictable stimuli do not depend on the starting level, at least for naive subjects.

Another consideration to differences with previous studies is that we used a step wave–modulated stimulus for all conditions, not sinusoidal as used in the studies described in Introduction. This procedural difference should not have an effect because when Heron et al.[35] and Heron and Charman[37] compared latency and accommodation response magnitude between step-modulated and sinusoidally modulated stimuli, they concluded that the responses were broadly comparable. Nevertheless, they did note that accommodation latencies at frequencies up to 1 Hz were greater for step

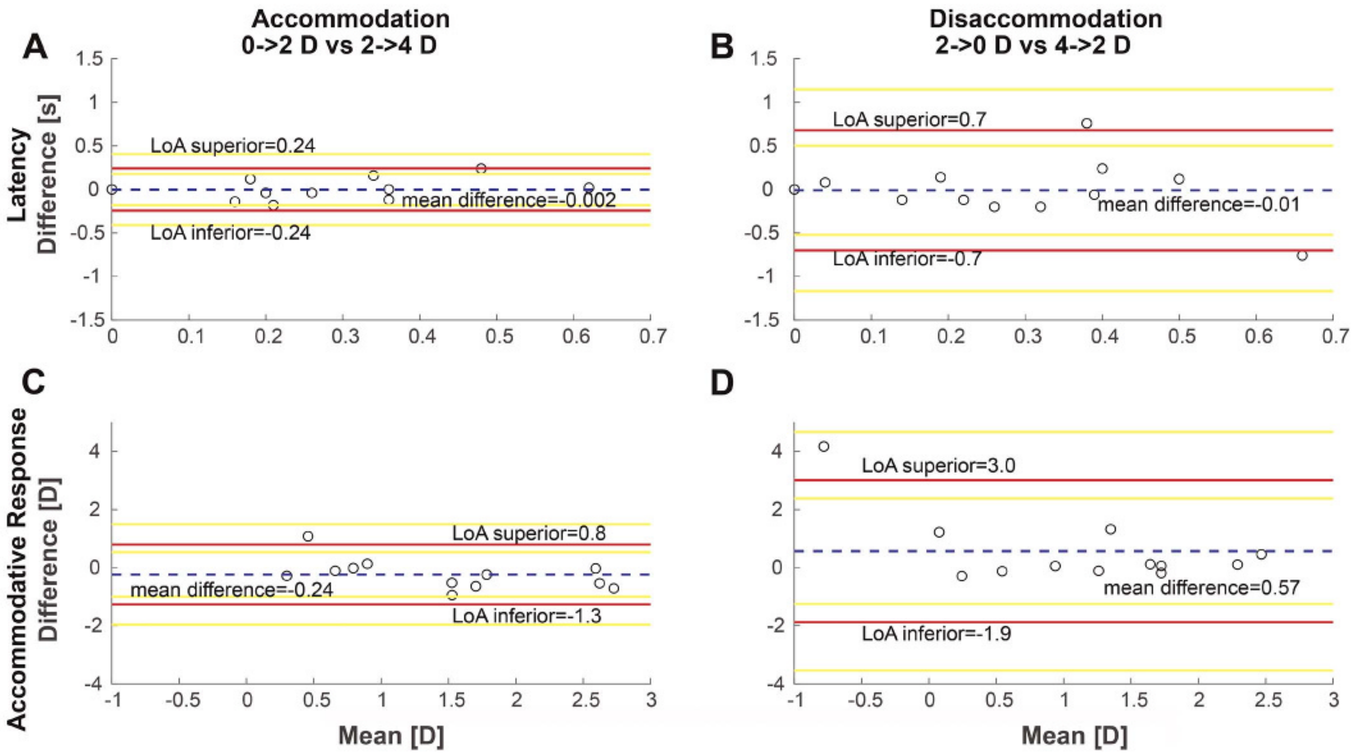

FIGURE 7. Bland and Altman plots comparing (A to B) latency and (C to D) accommodative response magnitude values obtained for two different starting points of accommodative demand: the transition in accommodative demand between 0 and 2 diopters and the transition between 2 and 4 diopters. Blue line, mean difference (value of the transition 0/2 diopters minus value of the transition 2/4 diopters); red lines, 95% limits of agreement; yellow lines, 95% confidence interval for both limits of agreement. Latencies and accommodative responses of both transitions are obtained from condition 2 (i.e., predictable in time, direction, and magnitude with 3 accommodative states).

wave–modulated stimuli than those found by other investigators using sinusoidally modulated stimuli, whereas other authors suggested that a sinusoidally moving target may not have much effect on the anticipation of accommodative response when blur is the only stimulus.[38]

More important than the type of modulation stimuli are subjected to may be the task instructed to the observers and whether they are naive or not. After a thorough review of previous studies that found an effect of stimulus predictability on accommodation,[1–3] it came to light that their results were obtained using limited sample sizes (four subjects[2] or one subject[1,3]), did not report whether participants were naive or not, and did not describe the specific task observers were instructed to perform. It is therefore difficult to compare our results with these studies because accommodation dynamics are affected by age,[8,9] refractive error,[10,11] and instructions.[12] We speculate that we did not find an effect of predictability in our study because (1) every observer was instructed to "clear the target" naturally, and (2) none of the participants were trained to perform voluntary accommodation, and all of them were naive to the purpose of the study. In our study, we did not control for the subjects' ability to perform voluntary accommodation. Kruger and Pola[39] suggested that voluntary control in the form of prediction and anticipation of accommodation may be a natural mode of the accommodative system. On the other hand, negative accommodation latencies found under predictable stimulus conditions in previous studies could be attributed to voluntary accommodation.[40] Our hypothesis is that anticipation affects accommodation only in experienced subjects who are instructed to purposely use voluntary accommodation in addition to reflex accommodation. This hypothesis is consistent with reports by Heron et al.,[35] who suggested that accommodative latencies obtained with predictable stimuli may tell us more about the training and alertness of the subjects than about the temporal abilities of the accommodation system.

In addition, the lack of appropriate accommodation cues can significantly alter the overall accommodative response when stimulated optically.[24] This may become relevant in the clinical monocular accommodation facility flipper test, where there are no disparity cues and blur cues do not match vergence; that is, blur changes, whereas the size-distance cue does not.[41] The neural cross-linkages between vergence and accommodation, which are subject to adaptive regulation,[42] may have played a role in the results of our study, as disparity is an important cue for distance.[43] However, it has been shown that voluntary efforts seem to primarily affect accommodation rather than vergence in the near response.[44] According to our results, the monocular accommodation facility clinical test would not be influenced by the predictability of the stimulus. Further studies should specifically address this question, unpredictable stimuli may give a better indication of dynamic accommodation performance under real-life conditions,[35] and increased accommodation facility with flippers may be more related to learning to accommodate in an unusual visual situation.[41]

Another interesting finding of our study is that subjects seemed to perceptually notice whether the stimulus was predictable or not, although accommodation responses and latency were not statistically significantly related to predictability. Despite that the differences between the perceived scores of predictable and unpredictable conditions were not statistically significant after the Bonferroni correction for multiple tests, nonsignificance is probably obtained provided that the Bonferroni procedure ignores dependencies among the data and is therefore much too conservative when the number of tests is large,[45] as it occurs in our study with 36 pairwise comparisons. It could be possible that the perceptual scores of predictability may not be necessarily indicative of the degree of predictability of the stimuli; hence, the lack of significant differences found in this study may also be caused by the unpredictable stimuli not being sufficiently unpredictable. Although the most unpredictable condition in this study (condition 9) comprised up to 54 different changes of accommodative demand that were randomly presented for 120 seconds in each subject, future studies could include unpredictable conditions with more random accommodative states.

CONCLUSIONS

The effect of predictability in changes of time, magnitude, and direction of the accommodation demand on the accommodation response latency and its magnitude is not significant. Our results did not find evidence for a strong prediction operator in a repetitive accommodative task where voluntary accommodation was not controlled; this suggests that the clinical accommodative facility test may not be influenced by potential anticipation effects.

ARTICLE INFORMATION

Supplemental Digital Content: Appendix Figure A1 (available at http://links.lww.com/OPX/A401). Comparison between the most predictable (no. 1) and unpredictable conditions (no. 9) for different inferior limits of the latency algorithm. The *y* axis is the number of cases where latency is <40 milliseconds. The *x* axis is the inferior limit set in latency algorithm; that it, we have allowed the algorithm to compute latencies from 0 (0 milliseconds), 1 (–40 milliseconds), 2 (–80 milliseconds)…, 14 samples (–560 milliseconds) before the starting position of each accommodative transition.

Appendix Table A1 (available at http://links.lww.com/OPX/A402). Median latency obtained for each subject and experimental condition in accommodation (0 to 2 diopters) and disaccommodation (2 to 0 diopter). ACC = accommodation; DIS = disaccommodation.

Appendix Table A2 (available at http://links.lww.com/OPX/A403). Median accommodative response obtained for each subject and experimental condition in accommodation and disaccommodation. ACC = accommodation; DIS = disaccommodation.

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