Predictability of Sinusoidal Stimulus Movement in Accommodative Demand Does Not Improve Accommodation

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Research Article

Keywords: predictable target motion, sinusoidal movement, accommodative response, Fatigue

Posted Date: March 22nd, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-329701/v1>

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Version of Record: A version of this preprint was published at Scientific Reports on July 26th, 2021. See the published version at <https://doi.org/10.1038/s41598-021-94642-2>.

Predictability of sinusoidal stimulus movement in accommodative demand does not improve accommodation

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ABSTRACT

Previous research work suggests that predictable target motion such as sinusoidal movement can be anticipated by the visual system, thereby improving the accommodative response. The validity of predictable motion for studying human dynamic accommodation is sometimes put into question. The aim of this work was to assess from a practical perspective the effect of anticipation along with learning (and motivation, etc.) and fatigue (and boredom, loss of attention, etc.) on dynamic accommodation experiments. Specifically, changes in amplitude and temporal phase were estimated within and between trials as 9 adult observers were instructed to focus on a stimulus that oscillated in distance at specific temporal frequencies. On average, amplitude decreased whereas phase increased within trials. No evidence of anticipation or learning was observed either within or between trials. Fatigue consistently dominated anticipation and learning within the course of each trial. Even if the eye is equipped by a “prediction operator”, in practice, it is fatigue, and not anticipation or learning, that seems to muddle the results from dynamic accommodation experiments.

Introduction

Dynamic accommodation studies typically use stimuli whose dioptric distance from the eye varies sinusoidally after some cues are removed^{1–6}. The impact of any specific optical cues, e.g., binocular disparity, chromatic and monochromatic aberrations, and optical defocus, is assessed by quantifying how well the eye follows the stimulus. Sine waves are the most used movement profiles because they are simple and easy to characterize and analyze. In addition to typical microfluctuations^{7,8} during accommodation, the response to a sinusoidal accommodative demand is also a sinusoid but typically with smaller amplitude and a greater temporal phase with respect to the demand^{4,5}.

Despite their popularity, the use of sinusoidal changes in accommodative demand for studying human dynamic accommodation has received some criticism due to the repetitive and predictable nature of the visual stimulus^{5,6}. More precisely, Stark et al.⁵ obtained a shorter time delay in accommodative responses to sinusoidal movements of the target than what they expected for the accommodative system. They pointed out that accommodation could be aided by a prediction operator when following a repetitive target motion such as a sinusoid. Van der Wildt and colleagues⁶ tried to devise whether anticipation of sinusoidal changes in accommodative demand was important. They reduced the predictability of the sinusoidal temporal profiles by adding noise and observed a systematic decrease in amplitude and increase in temporal phase for the distorted signals. They concluded that subjects were able to make use of anticipation when accommodating to the noise-free signal. On the other hand, Kruger et al.⁹ employed the sum of four sine waves with different temporal frequencies (0.1, 0.2, 0.3, and 0.4 Hz) and random temporal phases to produce non-predictable changes in target motion. They observed strong accommodative responses at the 0.1 Hz temporal frequency and contended that subjects were not simply responding to predictable rhythmical changes in the target.

In experimental settings, measurements of this kind are, however, susceptible to the confounding effects not only of predictability, but also of learning and fatigue effects. Learning effects lead to increased amplitudes and decreased temporal phase over time, whereas fatigue effects lead to the opposite, decreased amplitudes and increased temporal phase over time. The repercussion on the measurements is the cumulative effect of those individual elements. If fatigue effect is stronger than anticipation and learning effects, the amplitude of the accommodative response of participants would decrease over time within a trial and between trials, whereas temporal phase would increase. On the other hand, if anticipation and learning effects are stronger, amplitude would increase and phase decrease over time with a trial and between trials. Notice that, for the sake of simplicity, fatigue effect is used here as an umbrella term for all psychophysical and psychological factors that, as boredom and loss of attention, decrease observer's performance. Likewise, learning effect is an umbrella term for all factors that, as

motivation and level of attention, increase observer's performance.

The purpose of this work was to elucidate how anticipation, learning, and fatigue effects modulate the accommodative responses to sinusoidal changes in accommodative demand within and between trials. Does learning and anticipation lead to more accurate accommodation, or does fatigue reduce the accommodative responses?

Methods

Dynamic accommodation data

The data analyzed here was collected during an earlier study of human dynamic accommodation¹⁰ that examined whether monocular monochromatic accommodation is driven only by a trial-and-error mechanism to minimize blur¹¹ or if optical vergence (inverse of target distance) itself is an important cue for accommodation^{4,12}. A subset of their conditions employed sinusoidally moving stimuli generated with a custom adaptive-optics system^{13,14} that monitored participants' accommodative responses while correcting refractive error, astigmatism, and higher-order aberrations. Retinal image blur, hence, was only generated by accommodative inaccuracy, that is, if the accommodative response did not match the accommodative demand precisely. In more detail, participants viewed monocularly a monochromatic Maltese cross (550 ± 5 nm) through a 4-mm artificial pupil spanning 1.95° of visual angle and with a luminance of about 20 cd m^{-2} . The target moved sinusoidally at different speeds under different optical conditions. The experiments and conditions are explained in full detail in section 2.3 *Experimental conditions* and Figure 1 in¹⁰ and only the methods for the data selected here for analysis are summarized in the following.

Data were collected for a total of 9 eyes from 9 participants. The participants had an average (and SD) age of 27(6) years and their refractive errors ranged from -5.0 to $+0.5$ diopters (D), with a mean spherical refractive error of $-1.44(1.89)$ D. None of the participants had astigmatism greater than 1 D. Subjects were free from ocular pathologies and accommodation anomalies. The study was approved by the University of Valencia Ethics Committee and informed consent was obtained from each subject. Experiments were performed in accordance with relevant guidelines/regulations and with the Declaration of Helsinki.

The stimulus moved sinusoidally starting at 2 D towards and away from the eye between 1 D and 3 D at temporal frequencies of 0.05 Hz, 0.1 Hz, 0.2 Hz or 0.4 Hz. The initial direction of the target movement was random. The duration of the trials was different for different temporal frequencies (25 s for 0.2 Hz and 0.4 Hz, 30 s for 0.1 Hz, and 40 s for 0.05 Hz). Lower frequency trials had longer duration as to contain at least two cycles of the sinusoidal changes in accommodative demand. For each participant, each experimental condition was repeated 6 times. Therefore, there was a total of 24 trials (6 repetitions at each of the 4 temporal frequencies) per participant. As part of the recruitment process, preliminary trials were run to ensure that subjects could accommodate effectively to the monocular, monochromatic target without any optical manipulation, since about 15% to 35% of people cannot accommodate under these reduced cue conditions^{3,15,16}. These preliminary trials consisted of presentations of a stimulus moving sinusoidally at 0.2 Hz lasting for 25 s. For each participant, the preliminary experiment was repeated 6 times (as it was done with the experimental conditions outlined earlier). Data for these repeat trials were included here also for analysis. Accommodative response was calculated by finding the quadratic surface fit that minimizes the root mean square error of the wavefront and which is calculated with the Zernike defocus coefficient^{17,18}.

Systematic data analysis in¹⁰ consisted of fitting a sine wave to the accommodative response, r , to a moving stimulus with frequency f , amplitude a , and temporal phase p . Thus,

$$r = a \sin 2\pi f(t - p), \quad (1)$$

where the frequency f was 0.05 Hz, 0.1 Hz, 0.2 Hz or 0.4 Hz depending on the accommodative demand presented. Amplitude a and phase p were estimated using ordinary least squares. Note that this calculation is equivalent to performing a Fourier transform and collecting amplitude and phase at the frequency of interest¹⁹. Since only three subjects could follow the target when it moved at 0.4 Hz with sufficient reliability to study anticipation, learning, and fatigue effects —see Figure 5 of in¹⁰—, data for this condition was removed from the analysis. Therefore, data for 24 trials for each of 9 subjects were selected for analysis: 6 preliminary trials and 6 trials for the optical-blur condition with temporal frequencies 0.05 Hz, 0.1 Hz, 0.2 Hz.

Data analysis

Two analyses were carried out, one quantifying changes in amplitude and phase over trials and another quantifying changes in amplitude and phase over time within single trials. For the first, between-trial analysis only data from the preliminary trials was used. Data from the optical-blur condition were not included because the experimental design makes it impossible to obtain reasonable estimates of the changes in amplitude and phase over trials. The reason is that, unlike the preliminary condition that had its 6 repetitions at the same temporal frequency done in succession, trials with slow moving (0.05 Hz and 0.1 Hz) and fast moving (0.2 Hz and 0.4 Hz) stimuli were randomly intermixed among them and also with others from a different

experimental condition. Furthermore, because of the large amount of trials (48 in total), breaks during the experimental session were common, so that subjects could rest and follow the stimulus better. For the second, within-trial analysis, data from both the preliminary trials and the optical-blur conditions were used as the results are unaffected by trial order and breaks.

For the between-trial analysis, a linear mixed model was used to quantify how amplitude a , as estimated with (1), changed from trial to trial. The model was designed so that there was a common slope quantifying the overall change in amplitude over trials and a different intercept for each of the 9 participants. The Wald method was used to obtain the 95% confidence intervals for the slope representing the overall change in amplitude over trials. The same analysis was replicated for phase p as estimated with (1).

Figure 1. Sample trials for the different visual conditions. Each row shows a single trial. The left column shows the recorded accommodative response (dark gray dots) to a sinusoidally moving stimuli (blue curve) and the local-sinusoidal fit (black curve). The subject, condition, and repetition number are specified on the top of each graph. The middle column shows the amplitude of accommodation in D of the fit in the left column (open black circles) sampled at every 0.5 s, the line in gray was fitted with simple linear regression, and the first and second segments of the segmented regression in red and blue of a broken-stick model were fitted with segmented regression. The right column shows the same as the middle column but for phase in s.

For the within-trial analysis, changes in amplitude and phase were quantified by refitting the accommodative response over time for each trial with a sine wave function for which amplitude and phase was allowed to change over time thus,

$$r = a(t) \sin 2\pi f(t - p(t)), \quad (2)$$

where the amplitude and phase functions $a(t)$ and $p(t)$ were estimated with a loess-like approach²⁰ locally fitting a sine function as in (1) —instead of a linear or a polynomial function as is usual. The local-sinusoidal fits were obtained using Gaussian kernels with standard deviations corresponding to a fourth of each trial recording time; that is, 10 s, 7.5 s, and 6.25 s for signals recorded for 40 s, 30 s, and 25 s of accommodative responses to sinusoidally moving stimuli at 0.05 Hz, 0.1 Hz, and 0.2 Hz,

respectively. With this method and for each signal, amplitude a and phase p were estimated at each time t . These empirically obtained functions $a(t)$ and $p(t)$ were rendered by iteratively moving t by 0.1 s and estimating a and p in each step.

Each amplitude and phase function over time was then fitted a simple linear regression to extract the overall within-trial rate of change in amplitude and phase. A positive slope in amplitude or negative slope in phase would be consistent with anticipation and learning effects, whereas a negative slope in amplitude and positive slope in phase would be consistent with a fatigue effect.

There is no reason to think that anticipation, learning, and fatigue effects have to be consistent over time so that the amplitude and phase functions either increase or decrease monotonically. Nevertheless, simple linear regression can only capture the overall change due to the dominating effect over the whole trial. To assess whether the effects of anticipation and learning, and fatigue change over time, segmented linear regression fits with a single break point (commonly known as a broken-stick or hockey-stick model) were obtained for all trials.

All analyses were performed in MATLAB (Mathworks, Inc., Natic, MA, USA) and the open-source statistical environment R²¹. The R package lme4²² was used to obtain the estimates from the linear mixed model and corresponding 95% confidence intervals for the between-trials analysis. The package segmented²³ was used to obtain the segmented linear regression for the within-trial analysis.

Results

Table 1 shows the results of the linear mixed model fits for the between-trial analysis. According to the fitted models, there was a mild yet clear decrease in amplitude and an increase in phase on the preliminary trials, both significantly different from zero at a significance level of 0.05 as can be deduced from the confidence intervals.

	Slope	SE	95% CI
Amplitude	−0.019	0.005	(−0.030, −0.009)
Phase	0.016	0.007	(+0.002, +0.030)

Table 1. Results of the linear mixed model fits of change in amplitude of accommodative response with repetition number for the preliminary trials. Slope estimates are shown along with their corresponding standard errors (SE) and the 95% confidence intervals (CI). The units of the slopes are D per repetition for amplitude and s per repetition for phase.

Figure 1 shows four examples (one in each row) of individual response signals along with the corresponding simple and segmented regression analyses for both amplitude and phase over time. The first example corresponds to a trial for which amplitude increased over the whole run, as would be expected if anticipation and learning effects are predominant over fatigue effects. The second example corresponds to a trial for which the amplitude decreased over the whole run, as would be expected if fatigue effects dominate over anticipation and learning effects. The third example correspond to a trial displaying anticipation and learning effect up to a time after which fatigue takes over. The fourth example correspond to a trial displaying fatigue effect over the first half of the trial after which performance is roughly constant. The [supplemental material](#) contains all trials and all conditions along with the calculated amplitude and phase over time for a good accommodator, an average accommodator, and a poor accommodator.

The local-sinusoidal fits (black curves in Figure 1) were reliable, with only 3 showing clear discontinuities in the amplitude and phase functions as assessed from visual inspection of all 216 fits corresponding to the 24 trials for each of the 9 observers. The 3 discontinuities occurred for two subjects and for the same optical-blur condition for a moving stimulus at 0.2 Hz of temporal frequency. Changes in amplitude and phase were often non-monotonic, with only about half of the fits with simple linear regression explaining more than 85% of variance in amplitude (114 out of 216) and in phase (110 out of 216). On the other hand, fits from segmented regression with a single break point explained more than 85% of the variance in more than 95% of fits (207 out of 216 for both amplitude and phase).

Figure 2 shows, for each condition, the average rate of change in amplitude over subjects obtained with simple linear regression and the average over subjects of the proportion of times the slopes for each segment of the regression were positive from all 6 repetitions for each condition. Figure 3 shows the same as Figure 2 but for phase instead of amplitude.

For all conditions, amplitude decreased with time on average over the course of each trial (left panel of Figure 2) and that reduction occurred for most subjects in both at start (middle panel of Figure 2) and end (middle panel of Figure 2) of the trial, with the only exception of the 0.2 Hz optical-blur condition, for which the percentage of positive slopes in the second segment was slightly greater than 50%. Likewise, phase increased with time on average over the course of each trial (left panel of Figure 3) and that increment occurred for most subjects in both at the start (middle panel of Figure 3) and at the end (middle panel of Figure 3) of the trial.

Figure 2. Linear and segmented regression analyses of amplitude. The open circles in the left panel show the average slope estimates in amplitude of accommodation over trials of the preliminary condition and of the 3 optical-blur conditions for moving stimuli at 0.05 Hz, 0.1 Hz, and 0.2 Hz from simple linear regression. The individual slope estimates for each subject are represented as open gray circles, except for the three subjects in the [supplemental material](#) showcasing a good accommodator, an average accommodator, and a poor accommodator which are represented by circles with green, blue, and red background color respectively. The open circles in the middle and right panels show the average percentage of times the slope was positive for, respectively, the first and second regression segments. The individual percentages for each subject are represented as solid gray circles, except for the good, average, and poor accommodators in the [supplemental material](#), which are represented by solid green, blue, and red circles respectively. All solid black lines represent the 95% confidence intervals, each with lengths 2 times 1.96 times the standard error of the mean over all 9 subjects for each condition.

Discussion

Anticipation, learning, motivation, fatigue, boredom, and loss of attention are all confounding effects that may affect accommodative responses during extended and repetitive testing. Anticipation and learning have been argued to be especially important when dealing with predictable sinusoidal accommodative demands^{5,6}. However, in the present study, little direct evidence was found of improved responses due to anticipation and learning. On the contrary, declines in amplitude and increases in phase were observed most often. Linear regression for both amplitude and phase showed that fatigue dominated over any potential anticipation and learning effects over the course of each trial and across repeated trials. The observed fatigue effects were generally small with an overall decrease in amplitude of 0.02 D and increase in phase of 0.02 s per trial (Table 1) and from 0.01 D to 0.03 D (Figure 2) and from 0.01 s to 0.07 s (Figure 3) for every 10 s of trial run.

These results do not support the conclusions from Stark and colleagues⁵ or those from Van der Wildt et al.⁶. Stark et al.⁵ concluded that “when the [crystalline] lens follows simple target motions such as a single sinusoid it evidently is aided by a prediction operator”. This conclusion was based on the observation that latency (time of inactivity before the eye reacts) to step changes in accommodative demand was considerably greater than the temporal phase of sinusoidal changes. Such an inference is speculative, and fails to acknowledge the obvious differences between stimuli: one that abruptly generates a lot of blur (depending on step size) versus one that does so gradually. In addition, the number of subjects is unclear (seemingly two, “D. D.” and “J. R.”), yet there were large fluctuations in the decrease of temporal phase⁶.

The lack of power in Stark et al. study⁵ led Van der Wildt and colleagues⁶ to design an experiment to corroborate their conclusion. In order to check for the possibility of anticipation in the response, they removed the predictability of the input signal by masking the sinusoidal signal with enough noise for the subjects to recognize the signal. More precisely, they added Gaussian noise with a low-pass filter to up to 5 Hz. They concluded that the systematic decrease in amplitude and increase in phase was due to participants inability to anticipate the noisy signal. But, the decrease in amplitude and increase in phase could also be a consequence of the greater stress imposed on the ciliary muscle by demanding it to follow a stimulus that moved at times at much greater speeds (of up to 5 Hz). As calculated with the linear mixed model which estimates are presented in Table 1, amplitude clearly decreases and phase increases with temporal frequency of the accommodative demand. And as shown in Figure 5 of Marín-Franch et al.¹⁰, for a temporal frequency of 0.4 Hz, most subjects struggle to even follow the moving stimulus.

The approach taken here was far more practical and did not require masking the signal. Even if the accommodation control system really is “aided by a prediction operator”⁵, the results of this analysis point towards a fatigue effect dominating participants responses in these kinds of experiments.

Figure 3. Linear and segmented regression analyses of phase. Details as for Figure 2 but for slope estimates for phase, instead of amplitude.

There is evidence for fatigue being an important confounding factor for accommodation in other studies of accommodations. For instance, Lancaster and Williams²⁴ observed a decrease of power to accommodate after about half an hour of continuous near fixation. This observation was corroborated by another set of experiments by Berens and Sells²⁵, who also studied fatigue of accommodation binocularly and monocularly, while the contralateral eye was patched, and found that both eyes manifested fatigue, even the occluded one. In yet another series of experiments, it was demonstrated that tonic accommodation is reduced after performing a repetitive accommodative task using a lens flipper due to accommodative fatigue²⁶. Sharmin and Vohnsen found that fatigue increased the accommodation response time to step-changes in demand by up to three times²⁷. There is also evidence against fatigue effects. One study observed that the amplitude of the accommodation did not seem to change systematically during 30 minutes of repetitive accommodation tasks following step changes²⁸, but responses were highly variable and only two subjects were tested. Note that the data analyzed here are not from experiments that are directly concerned with the effects of training^{29–31} and that have been shown that it can improve accommodation. Unlike for experiments exploring the effects of weeks long training³¹, the trials here were all done on the same day. Therefore, the results of this study are not comparable with those in³¹.

The results of this work are based on the use of the Zernike defocus term as a proxy for accommodative response. Other methods could have been used to calculate the accommodative response instead that yielded different results. One such method is the paraxial curvature matching method¹⁸, which is based on paraxial optics and what has become known as Seidel refraction. Although Lara et al.³² found a greater amplitude of accommodation to a sinusoidal moving stimulus using Seidel refraction, the trend among subjects and conclusions drawn from both analyses were essentially the same. Likewise, a similar conclusion would be expected here had the Seidel refraction been used instead of the Zernike defocus term.

The analysis reported here differed from that of Marín-Franch et al.¹⁰ in that amplitude and temporal phase was calculated over time in each trial, using a loess-like approach locally fitting a sine function. Nevertheless, the results obtained with this new and more sophisticated analysis are consistent with the ones obtained with the original analysis. The mean difference across subjects between the two analyses when the stimulus moved following a sinusoidal with frequencies of 0.05 Hz and 0.1 Hz was lower than 0.02 D (with a maximum difference 0.03 D); and for a frequency of 0.2 Hz, the mean difference was lower than 0.01 D (with a maximum difference 0.02 D). These differences are very small and do not change the significance and conclusions of the original, simpler analysis.

Contrary to what previous work suggested^{5,6}, accommodative responses to repetitive sinusoidal changes in accommodative demand are dominated by fatigue confounding effects rather than by anticipation and learning. If anticipation to predictable changes in accommodative demand exists, it is outweighed by fatigue effects. This supports the notion that complex experimental designs aimed at avoiding learning effects may only unnecessarily add burden to subjects.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Acknowledgements

We thank David H Foster for suggesting the use of a modified loess analysis for the within-trial learning and fatigue effect.

Author contributions statement

AJDAC and IMF wrote the main manuscript text and performed the analyses. IMF prepared the figures. All authors reviewed the manuscript

Additional information

Competing interests The authors declare no competing interests.

Figures

Figure 1

Sample trials for the different visual conditions. Each row shows a single trial. The left column shows the recorded accommodative response (dark gray dots) to a sinusoidally moving stimuli (blue curve) and the local-sinusoidal fit (black curve). The subject, condition, and repetition number are specified on the top of each graph. The middle column shows the amplitude of accommodation in D of the fit in the left column (open black circles) sampled at every 0.5 s, the line in gray was fitted with simple linear regression, and the first and second segments of the segmented regression in red and blue of a broken-stick model were fitted with segmented regression. The right column shows the same as the middle column but for phase in s.

Figure 2

Linear and segmented regression analyses of amplitude. The open circles in the left panel show the average slope estimates in amplitude of accommodation over trials of the preliminary condition and of the 3 optical-blur conditions for moving stimuli at 0.05 Hz, 0.1 Hz, and 0.2 Hz from simple linear regression. The individual slope estimates for each subject are represented as open gray circles, except for the three subjects in the supplemental material showcasing a good accommodator, an average accommodator, and a poor accommodator which are represented by circles with green, blue, and red background color respectively. The open circles in the middle and right panels show the average percentage of times the slope was positive for, respectively, the first and second regression segments. The individual percentages for each subject are represented as solid gray circles, except for the good, average, and poor accommodators in the supplemental material, which are represented by solid green, blue, and red circles respectively. All solid black lines represent the 95% confidence intervals, each with lengths 2 times 1.96 times the standard error of the mean over all 9 subjects for each condition.

Figure 3

Linear and segmented regression analyses of phase. Details as for Figure 2 but for slope estimates for phase, instead of amplitude.

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