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ORIGINAL ARTICLE

Is 25 Hz enough to accurately measure a dynamic change in the ocular accommodation?

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KEYWORDS
Accommodation;
Sampling rate;
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Main sequence

Abstract
Background: Accommodation is often recorded at a low sampling rate using devices such as autorefractors that are designed to measure the static refractive error. It is therefore important to determine if that resolution is sufficient to accurately measure the dynamic properties of accommodation. The current study provides both theoretical and empirical evidence on the ideal sampling rate necessary to measure a dynamic response.
Methods: Accommodative and disaccommodative step stimuli ranging from 1–3D (1D steps) were presented using a Badal optical system. Responses from 12 children (8–13 years) and 6 adults (20–35 years) were recorded using a dynamic photorefractor (DPR). Fast Fourier transformation was applied to the unsmoothed dynamic responses including position, velocity and acceleration. Also, velocity and acceleration main sequence (MS) characteristics were compared between three photorefractor conditions on 3 subjects.
Results: The Nyquist sampling limit necessary to accurately estimate position, velocity and acceleration was at least 5, 10 and 70 Hz, respectively. Peak velocity and acceleration were significantly underestimated at a lower rate ($p < 0.5$). However, the slope of MS remained invariant with sampling rate ($p > 0.5$).
Conclusion: Contrary to the previous findings, a dynamic accommodative response exhibited frequencies larger than 10 Hz. Stimulus direction and amplitude had no influence on the frequencies present in the dynamic response. Peak velocity and acceleration can be significantly underestimated when sampled at a lower rate. Taken as a whole, low sampling rate instruments can accurately estimate static accommodation, however, caution needs to be exercised when using them for dynamic accommodation.

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PALABRAS CLAVE
Acomodación;
Tasa de muestreo;
Frecuencia;
Transformación de Fourier;
Tasa de Nyquist;
Características dinámicas

¿Son suficientes 25 Hz para medir con precisión un cambio dinámico en la acomodación ocular?

Resumen La acomodación se registra a menudo a una tasa de muestreo baja, utilizando dispositivos tales como los autorrefractómetros que están diseñados para medir el error refractivo estático. Por tanto, es importante determinar si dicha resolución es suficiente para medir con precisión las propiedades dinámicas de la acomodación. El estudio actual aporta evidencia tanto teórica como empírica acerca de la tasa de muestreo necesaria para medir una respuesta dinámica.
Métodos: Se presentaron estímulos de alteraciones de estimulación y relajación (desacomodación) de la acomodación que oscilaron entre 1 y 3D (pasos de 1D) utilizando un sistema óptico Badal. Se registraron las respuestas de 12 niños (de 8 a 13 años) y 6 adultos (de 20 a 35 años) utilizando un sistema de fotorrefracción dinámico (DPR). La transformación rápida de Fourier se aplicó a las respuestas dinámicas no uniformes incluyendo posición, velocidad y aceleración. También se compararon las características de la secuencia principal de velocidad y aceleración entre las tres situaciones del sistema de fotorrefracción en 3 sujetos.
Resultados: El límite de muestreo de Nyquist necesario para calcular con precisión la posición, velocidad y aceleración fue de al menos 5, 10 y 70 Hz respectivamente. La velocidad y aceleración máximas se subestimaron significativamente a una tasa inferior ($p< 0,5$). Sin embargo, la pendiente de la secuencia principal permaneció invariable con la tasa de muestreo ($p>0,5$).
Conclusión: Contrariamente a los hallazgos anteriores, la respuesta acomodativa dinámica mostró unas frecuencias superiores a 10 Hz. La dirección y amplitud del estímulo no influyeron en las frecuencias presentes en la respuesta dinámica. La velocidad y aceleración máximas pueden subestimarse significativamente cuando se muestrean a una tasa menor. En conjunto, los instrumentos de baja tasa de muestreo pueden calcular con precisión la acomodación estática; sin embargo, debe actuarse con precaución a la hora de calcular la acomodación dinámica.

Introduction

Accommodation is a dynamic change in the curvature of the crystalline lens allowing the eye to focus objects at various distances. Static and dynamic characteristics of accommodation have been well established on human subjects and other primates.[1–8] Various instruments such as autorefractors, infrared optometers and photorefractors have been commonly employed to measure accommodation.[1–3,9–12] However, most of these instruments were manufactured to measure refractive errors (or static accommodation). Previous studies on accommodative microfluctuations found that frequencies that are of accommodative origin were typically less than 5 Hz (this work was cited by Campbell[13] but the original work was a French publication by Arnulf et al.[14]). They concluded that to record the dynamic steady state errors accurately, optometers should operate at a sampling rate of at least 10 Hz. Accordingly, various autorefractors and optometers have been redesigned to work at an appropriate sampling rate to measure these dynamic accommodative changes.[9,10,13,15,16] The influence of factors such as age, refractive error, stimulus demand, and depth of focus on accommodative microfluctuations has been well established.[2,8,17–19] Other dynamic parameters such as velocity and acceleration also have been measured using a wide range of instruments (operating at rates ranging from 25 Hz to 200 Hz).[1,3] Given the evidence on microfluctuations, sampling rate should not affect these measures. However, it is unknown whether the frequency spectra from the steady state errors applies to the first and second order dynamics of accommodation and disaccommodation.

Accordingly, two studies were designed to estimate the ideal sampling frequency required to measure accommodative position, velocity and acceleration accurately.

Study I: Spectral analysis of dynamic accommodation

The first study used Fast Fourier transformation[20] to quantify the ideal sampling rate necessary to accurately measure the dynamic characteristics of both accommodation and disaccommodation.

Methods

12 children (8–13 years) and 6 naive adults (age: 20–35 years) were recruited from the clinic database at the School of Optometry and Vision Science, University of Waterloo. Informed consent was obtained from the parents for a child and was obtained directly from the adult subjects. The study followed the tenets of Declaration of Helsinki and received ethical approval from the University of Waterloo office of research ethics review board. Subjects with strabismus, amblyopia, anisometropia >1.00D, astigmatism >1.00D and with best corrected visual acuity of less than 6/6 were

excluded. All the subjects with refractive error were habitual contact lens wearers and wore the lens during the study.

Instrumentation

Dynamic photorefractor (DPR, PROSILICA CAM (EC750), Allied Vision Technologies, BC, Canada) was a custom built eccentric photorefractor used to measure accommodation and disaccommodation. This system has been described elsewhere.[21] The sampling rate of the system was 70 Hz, giving an output every 14 ms. Accommodation data were then loaded into the dynamic photorefraction system (DPRS) for further analysis.[21] DPRS was calibrated and validated on children and adults.[22] Individual calibration procedure followed in this study was similar to those described previously.[11,23] This was done to address the individual variation in the optical factors such as pupil size, fundus reflectance etc. and ensure accuracy in estimating changes in the accommodation state.

Experimental design

Accommodation was stimulated using a Badal optical system.[24] As shown above (Fig. 1), the subject was seated 1 m away from the photorefractor. An IR passing mirror (Optical cast IR filter, Edmund Optics, USA) in front of the subject allowed an orthogonal presentation of the step targets along with a continuous measure of accommodation using the photorefractor. Two high contrast targets (T1, T2; black on white vertical lines that were illuminated using white LEDs) were placed at different distances from a +5D Badal lens to create various accommodative and disaccommodative demands without a change in the angular size of the target. While the far target was always at infinity, near one was moved to various distances to create demands ranging from 1-3D, 1D steps. The accommodative demand was instantly switched from one distance to the other using a stimulus control tool box with a button. This switch was connected to the dynamic photorefraction system through an input–output control box allowing a time stamp to be created with the onset of the stimulus. Stimulus order and presentation time was randomized to avoid predictability or learning effects.

Procedure

After an initial assessment of the anterior chamber, both eyes of each subject were dilated using 2.5% Mydfrin (Phenylephrine hydrochloride). This was done to optimize the photorefraction measures by providing a larger pupil size (>4 mm). The left eye was occluded throughout the experiment to open the loop of the vergence system. Practice trials were given in order to familiarize the subjects with the procedures involved. Single step responses to both accommodation and disaccommodation were presented using a Badal system and recorded using the photorefractor. Multiple trials (ranging from 6 to 12) were conducted for each stimulus level of accommodation and disaccommodation and each trial lasted for 5–10 s. The stimulus presentation time was varied from 2 to 5 s after the initiation of the trial to avoid prediction. Frequent breaks were given to both children and adults between the trials to avoid fatigue effects on accommodation and disaccommodation.

Data analysis

Final position traces (units of diopters) obtained from the DPRS were used for further dynamic analysis on MATLAB (Mathworks, Inc., MA, USA). Velocity (diopters/s) and acceleration (diopters/s^2) profiles were obtained by differentiating the response traces using a 2-point-difference algorithm. Velocity threshold criterion[1] was used to identify start and end points of the dynamic accommodative response. An inverse of this criterion was used for disaccommodative responses.

Fourier transformation (FFT) was then applied on the individual unsmoothed position, velocity and acceleration traces obtained from all the subjects. As shown in Fig. 2, FFT was applied only to the dynamic response between the two red dotted lines i.e. between the start and end points of the response. Ideal sampling rates for measuring the accommodative and disaccommodative position, velocity

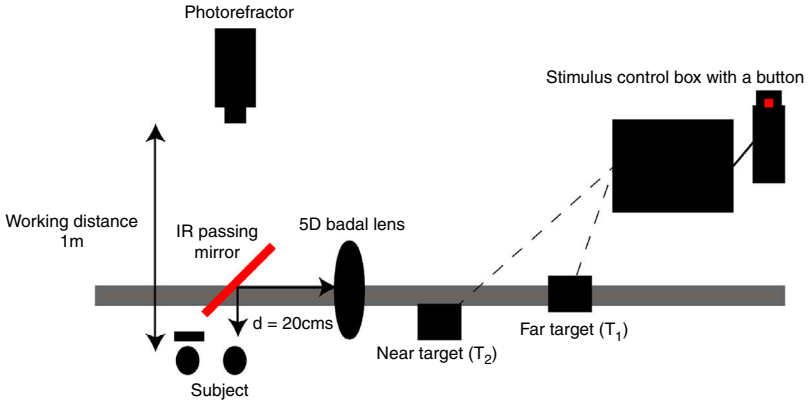

Figure 1 Experimental design to stimulate accommodation and disaccommodation. The subject was seated 1 m away from the photorefractor with the left eye occluded. An IR passing mirror (Optical cast IR filter, Edmund Optics, USA) was placed in front of the right eye for an orthogonal presentation of the accommodative targets along with a continuous measure of accommodation using the dynamic photorefractor. High contrast targets (T1, T2) were placed at different distances from the +5D Badal lens to create various accommodative and disaccommodative demands. Step stimuli were presented using a stimulus control tool box with a button that helps in switching the target distance instantly.

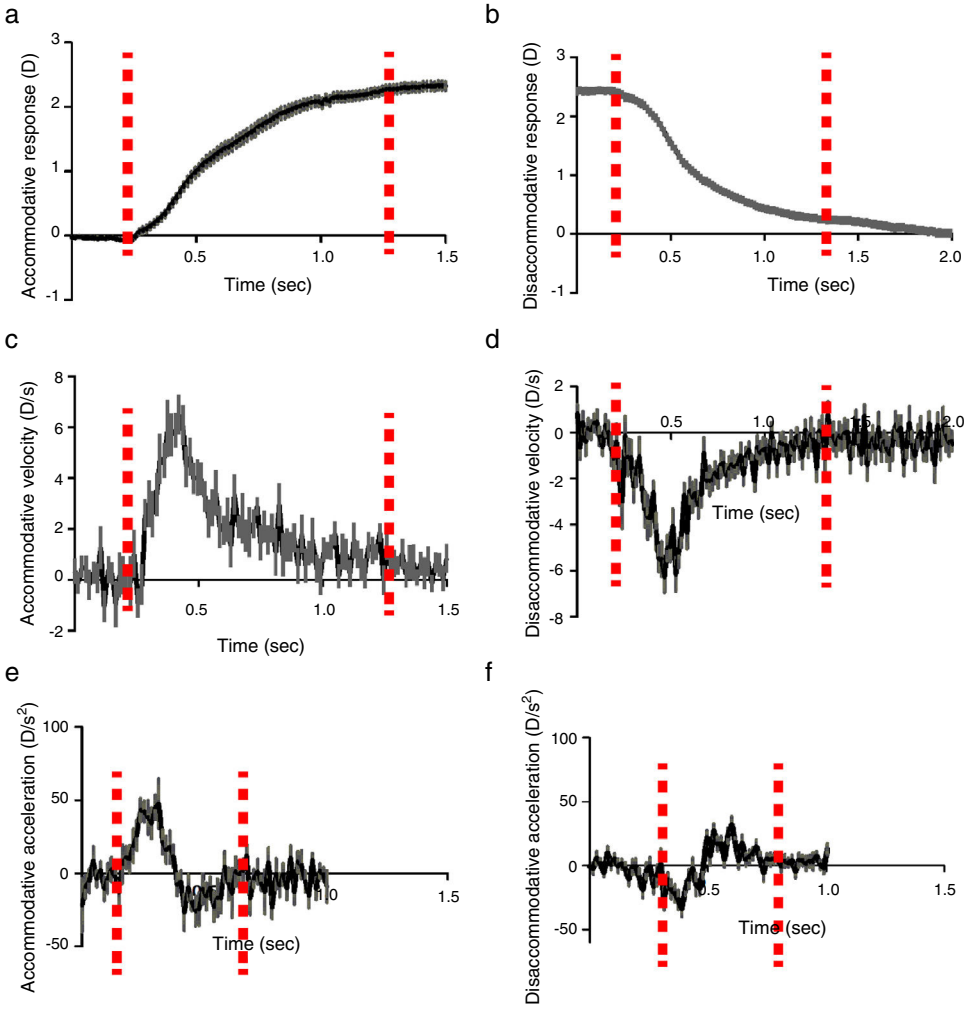

Figure 2 Typical dynamic accommodative and disaccommodative traces obtained from the subjects for a 3D stimulus. The solid line indicates the mean vlaue and shaded area indicates the standard error in the reponse. The red dotted lines indicate the start and end points of the dynamic traces and FFT was applied only on this area.

and acceleration traces were estimated using the peak frequency obtained from FFT. Instrument or measurement noise was identified by applying Fast Fourier transform on the measurements with a static model eye. The power spectrum due to noise was removed from the final accommodation frequency data to ensure that the measures were valid (Fig. 3) and only frequencies with a power spectrum larger than this limit were considered to be accommodative origin.

Results

Accommodation data were obtained from 12 children (11.16 ± 1.83 years) and 6 adults (26.16 ± 3.37 years). Fig. 3 shows the FFT output (mean and SE) obtained from unsmoothed accommodative and disaccommodative traces (mean and SE) measured across different accommodative demands (1-3D, 1D steps). The typical frequencies present in a dynamic position and velocity trace were limited to frequencies less than 10 Hz. For acceleration, frequencies ranging from 15 to 35 Hz were present. The ideal sampling rate (Nyquist rate) was calculated using the peak frequency present in the response. As shown in Fig. 3, stimulus direction (accommodation or disaccommodation) and demand (1/2/3D steps) had no influence on the range of frequencies present in a dynamic response. Based on the FFT data, the ideal sampling rate should be 5 Hz, 10 Hz and at least 70 Hz to accurately measure accommodative position, velocity and acceleration respectively.

Study II: Effect of sampling rate on the main sequence characteristics of velocity and acceleration

Important parameters characterizing a dynamic response are velocity, acceleration, duration, and amplitude. Relationship between these parameters can be quantified using the first (velocity) and second order (acceleration) main sequence analysis. Main sequence (MS) relationship has been commonly used to describe the dynamic aspect of a motor system.[1,3,24–26] It is the rate of change of velocity or acceleration as a function of the response amplitude. The slope of the MS profile defines the ability of the dynamic motor system. Studies looking at first or second order main sequence

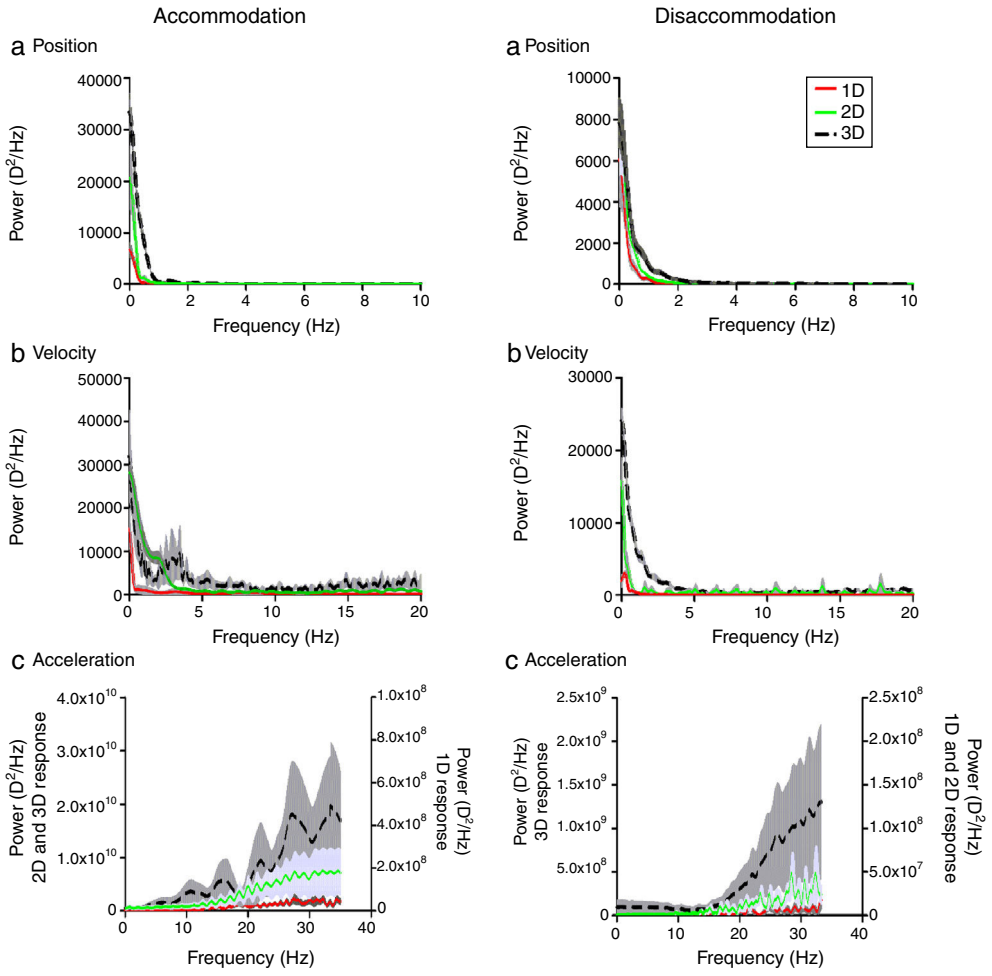

Figure 3 Fourier analysis of dynamic accommodation and disaccommodation. Unsmoothed time domain traces of position (a), velocity (b) and acceleration (c) obtained were converted into frequency domain using fast Fourier analysis across different accommodative demands, 1D (red line), 2D (green line) and 3D (black dotted line). The connecting lines indicate the mean values and shaded area indicates the standard error.

characteristics have used instruments that sample over various frequencies ranging from 25 Hz to 200 Hz. The present study compares three photorefractor conditions to understand the impact of sampling rate on the main sequence relationship.

Methods

Three adult subjects (26, 28 and 32 years) were recruited later for the second study where the dynamic main sequence was compared when measured at different sampling rates. Informed consent was obtained separately for this study visit. For main sequence comparison,

- Accommodation was measured on the 3 subjects using two separate photorefractors, a custom built eccentric DPR (70 Hz) and a commercially available PowerRefractor (25 Hz) on two separate days. The order was randomized.
- Accommodation was recorded using the Dynamic photorefractor (DPR). Data were subsequently analyzed at two sampling rates. First, the data were analyzed at its original sampling rate (DPR – 70 Hz). It was then down sampled to 30 Hz and the dynamic measures were re-analyzed (DPR – 30). This was done to understand the influence of differing analysis algorithms that might occur with the previous analysis.

Instrumentation

Dynamic photorefractor (DPR, PROSILICA CAM (EC750), Allied Vision Technologies, BC, Canada): As described in the first section (study 1).

PowerRefractor (PR, Multichannel systems, Reutlingen, Germany) is a commercially available photorefractor that works at a sampling rate of 25 Hz, providing an output every 40 ms. Numerous studies[3,27,28] have used it to measure static and dynamic characteristics accommodation on both children and adults. This was one of the first few photorefractors to successfully calibrate the optical principle of eccentric photorefraction for use in measures of accommodation.

Experimental design and procedures

The design used was similar to that described above. Similar procedures (as in study 1) were followed on two separate visits while accommodation data from the three subjects were recorded using the two photorefractors.

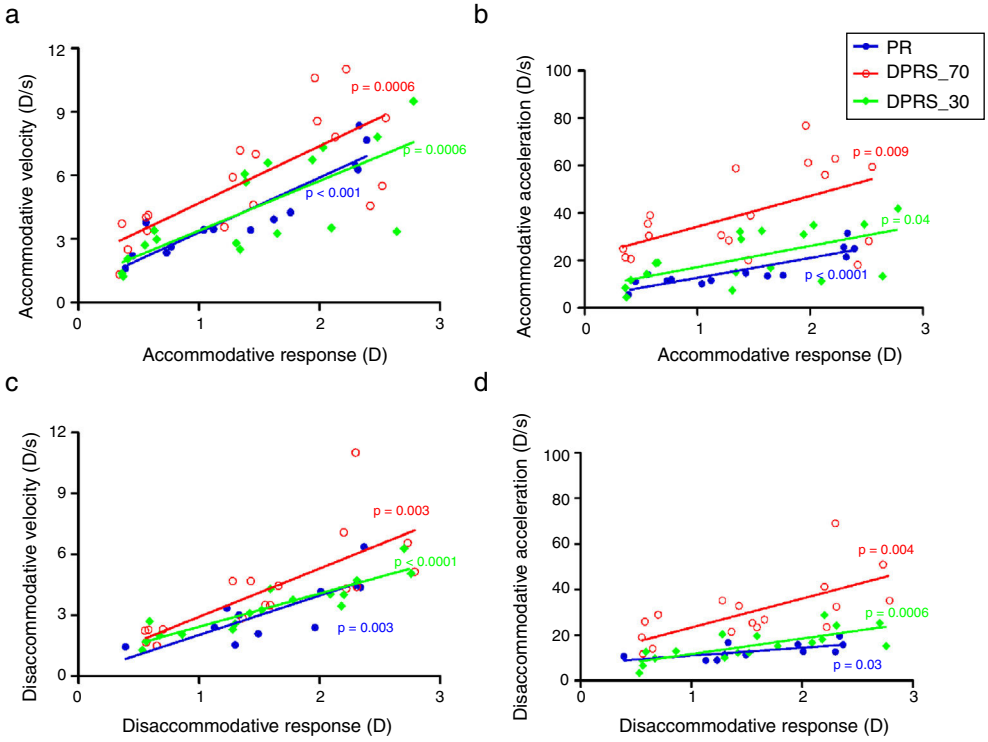

Figure 4 Main sequence data were compared between PR (blue) and DPR 70 (red) and DPR 30 (green). Deming regression was used to fit the MS data of velocity and acceleration for both accommodation (a, b) and disaccommodation (c, d). *p* value shows the difference between the slope of the regression fits from a zero slope.

Data analysis

Dynamic accommodative and disaccommodative position traces obtained from the DPR were then loaded into MATLAB for further analysis. Velocity (diopters/s) and acceleration (diopters/s^2) profiles were obtained by differentiating the response traces using a 2-point-difference algorithm. All the traces were subsequently smoothed using a 100 ms window. Velocity threshold criterion was used to identify the start and end of the response. The start of the response was the first point where the velocity exceeded 0.5 D/s and continued to do so for the next 100 ms. Similarly, end of the response was identified as the point where velocity fell below 90% of peak velocity and continued to do for the next 100 ms. The start and the end points obtained using this criterion were later confirmed by visual inspection.[1]

Accommodative response (D) was defined as the dioptric difference between the start and end points. Highest values on the velocity and acceleration traces were defined as the peak velocity (D/s) and peak acceleration (D/s^2) respectively. ''First order main sequence'' relationship was defined by plotting the accommodative and disaccommodative peak velocities as a function of their respective response amplitudes. Similarly ''Second order main sequence'' relationship was peak acceleration as a function of the response amplitude. Historically, linear regression was used to identify the main sequence relationship. However, given the variability in the velocity/acceleration and amplitude measures, a bivariate regression analysis such as Deming regression was chosen in the current study. Regression and other statistical analysis were performed using GraphPad Prism (GraphPad Software Inc., USA).

Results

Accommodative traces were obtained on three adults (26, 28 and 32 years). Fig. 4 shows the main sequence characteristics of both accommodation and disaccommodation obtained from the three photorefractor conditions.

For accommodation (Fig. 4(a) and (b)), Deming regression slopes of velocity and acceleration were significantly different from zero ($p < 0.01$). For accommodative velocity, the MS slopes were similar between the three conditions (DPRS (70 Hz): $2.69x + 2.05$; PR: $2.58x + 0.73$; DPRS (30 Hz): $2.34x + 1.06$; PR: $2.58x + 0.73$; Slopes: $F_{2,66} = 0.120$; $p = 0.88$). However, the intercepts were significantly lower ($F_{2,68} = 4.653$; $p = 0.01$) with PR ($p = 0.01$) and DPRS 30 ($p = 0.02$). Similarly, for accommodative acceleration, the MS slopes were similar between the three measurements (PR: $8.40x + 4.32$; DPRS 70: $12.93x + 21.38$; DPRS 30: $8.93x + 8.31$; Slopes: $F_{2,66} = 0.164$; $p = 0.84$) but the intercepts were significantly lower ($F_{2,68} = 19.79$; $p < 0.0001$) with PR ($p < 0.0001$) and DPRS 30 ($p < 0.0001$). For disaccommodative velocity (Fig. 4(c)), the MS slopes of velocity were similar between the three photorefractor conditions (PR: $1.94x + 0.09$; DPRS 70: $2.38x + 0.55$; DPRS 30: $1.63x + 0.80$; Slopes: $F_{2,56} = 0.686$; $p = 0.50$). However, the intercepts were significantly lower ($F_{2,58} = 4.017$; $p = 0.02$) with PR ($p = 0.04$) and DPRS 30 ($p = 0.04$). For disaccommodative acceleration, the MS slopes were similar between the three photorefractor conditions (PR: $3.46x + 7.52$; DPRS 70: $12.70x + 10.72$; DPRS 70: $6.82x + 4.93$; Slopes: $F_{2,56} = 2.130$; $p = 0.13$) but the intercepts were significantly lower ($F_{2,58} = 24.145$; $p < 0.0001$) with PR and DPRS 30 ($p < 0.0001$).

Discussion

Accommodation and disaccommodation data were successfully measured from both children and adults. Two separate studies were conducted to understand the ideal sampling frequency necessary to capture the dynamic behavior of accommodation accurately.

Study I

FFT was used to transform the time domain dynamic accommodative and disaccommodative responses into frequency domain. The peak frequency present in each dynamic response was identified and then used to calculate the ideal sampling rate required to avoid aliasing. In agreement with a previous investigation,[14] position and velocity data showed frequencies less than 5 Hz. However, we did found higher frequencies in the some dynamic accommodation and disaccommodation responses (such as acceleration). Frequencies present in a dynamic response were similar in both accommodation and disaccommodation. Also, frequencies present in a particular dynamic response (position, velocity or acceleration) appeared to be independent of the stimulus demand (Fig. 3). To measure accommodative position, velocity and acceleration accurately, the sampling rate should be at least 5 Hz, 10 Hz and at least 70 Hz respectively. For acceleration, we suspect that frequencies higher than 35 Hz may have been present in the response as our analysis was limited with our instrument's sampling rate (70 Hz).

Influence of noise on accommodation

The frequency spectra present in the dynamic responses such as velocity and acceleration were consistent for both accommodation and disaccommodation. Frequency data obtained using FFT can be corrupted by two types of noise, system (plant and neural) noise and measurement noise. In agreement with the previous studies,[29,30] accommodative position and velocity traces had frequencies less than 10 Hz. However, acceleration traces showed frequencies larger than 10 Hz. Given that accommodation is an overdamped mechanism, it is possible that higher frequencies might have occurred as a result of plant noise, especially in the acceleration measures. However, it is difficult to isolate plant/neural noise at this point due to the technological limitations. The influence of measurement noise was identified by applying FFT on the measurements using a static model eye. Given the stochastic nature of the noise, it is difficult to say that the potential influence of noise on the dynamic measures specifically accommodative velocity and acceleration was completely eliminated. However, efforts were made to minimize the influence of noise on the dynamic accommodative measures of velocity and acceleration. Velocity and acceleration traces were obtained by mathematically differentiating the position trace as it was not possible to simulate these dynamic traces using a model eye. Therefore, in the model eye simulation, first and second order dynamic noise spectrum was measured by differentiating the noise spectrum of the position trace. The influence of measurement noise was minimized by simply subtracting noise (frequency) data from the actual frequency spectra of the dynamic accommodative traces (Fig. 5).

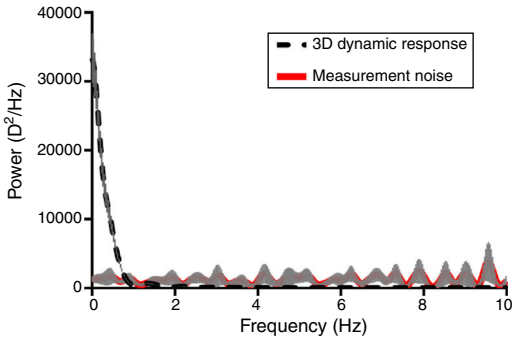

Figure 5 Fourier analysis of dynamic accommodative response to a 3D step stimulus (dotted line). Unsmoothed time domain traces of accommodative position obtained were converted into frequency domain using fast Fourier analysis (FFT). Instrument or measurement noise was identified by applying Fast Fourier transform on the measurements with a static model eye (red line). The power spectrum due to noise was removed from the final accommodation frequency data to ensure that the measures were valid. The connecting lines indicate the mean values and shaded area indicates the standard error.

Study II

Main sequence characteristics were compared between the two photorefractors that operate at different sampling rates. As we pointed out before, noise might have influenced the dynamic measures of accommodation especially when measured at 25 Hz. This is based on the fact that the FFT data showed larger frequencies with the acceleration traces suggesting a larger Nyquist frequency to accurately measure acceleration. Response analysis and smoothing procedures employed in this study were based on the dynamic signal to noise ratio (SNR) computations reported previously.[1,31] Therefore, the first and second order measures of accommodation obtained at a sampling rate of 70 Hz are assumed to be accurate with a minimal influence of noise. Peak velocity and acceleration dynamics were significantly underestimated when sampled at 25 Hz as shown by the difference in the intercepts ($p < 0.05$). Although FFT data on velocity traces showed frequencies <10 Hz, it is unclear at this point why peak velocity was significantly underestimated at lower sampling rates (25 Hz). Interestingly, the slope ($p > 0.10$) of main sequence appeared to be independent of the sampling rate suggesting that level of underestimation was consistent across all the stimulus demands presented during the course of this experiment. This confirms our FFT finding of similar frequencies being present in a particular dynamic response irrespective of the stimulus demand presented. Furthermore, the data also confirms that the previous measures of the velocity and acceleration main sequence characteristics are accurate[3,32,33] although the absolute values of peak velocity and peak acceleration might have been underestimated. Higher frequencies obtained in the FFT data might be questionable at this point given that the plant noise was not isolated, however, empirical evidence obtained from the second study suggests that low sampling instruments such as

autorefractors and photorefractors working at 25 Hz can significantly underestimate the first and second order dynamic behavior of accommodation.

Conclusion

Commercially available autorefractors and other low sampling rate instruments such as Power refractor (25 Hz) can be employed to measure refractive state, static accommodation and its steady state errors. When they are used to measure accommodative dynamics, peak velocity and acceleration will be significantly underestimated. However, since the underestimation was consistent across the response level, it does not affect the first and second order main sequence relationship.

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Conflicts of interest

The authors have no conflicts of interest to declare.

References

1. Bharadwaj SR, Schor CM. Acceleration characteristics of human ocular accommodation. *Vis Res*. 2005;45:17–28.
2. Candy TR, Bharadwaj SR. The stability of steady state accommodation in human infants. *J Vis*. 2007;7:4.1–16.
3. Kasthurirangan S, Glasser A. Influence of amplitude and starting point on accommodative dynamics in humans. *Invest Ophthalmol Vis Sci*. 2005;46:3463–3472.
4. Morgan MW. Accommodation and vergence. *Am J Optom Arch Am Acad Optom*. 1968;45:417–454.
5. Sun FC, Stark L, Nguyen A, Wong J, Lakshminarayanan V, Mueller E. Changes in accommodation with age: static and dynamic. *Am J Optom Physiol Opt*. 1988;65:492–498.
6. Vilupuru AS, Glasser A. Dynamic accommodation in rhesus monkeys. *Vis Res*. 2002;42:125–141.
7. Baumeister M, Wendt M, Glasser A. Influence of amplitude, starting point, and age on first- and second-order dynamics of edinger-westphal-stimulated accommodation in rhesus monkeys. *Invest Ophthalmol Vis Sci*. 2010;51:5378–5390.
8. Charman WN, Heron G. Microfluctuations in accommodation: an update on their characteristics and possible role. *Ophthalmic Physiol Opt*. 2015;35:476–499.
9. Wolffsohn JS, O'Donnell C, Charman WN, Gilmartin B. Simultaneous continuous recording of accommodation and pupil size using the modified Shin-Nippon SRW-5000 autorefractor. *Ophthalmic Physiol Opt*. 2004;24:142–147.
10. Win-Hall DM, Houser J, Glasser A. Static and dynamic measurement of accommodation using the Grand Seiko WAM-5500 Autorefractor. *Optom Vis Sci*. 2010;87:873–882.
11. Suryakumar R, Meyers JP, Irving EL, Bobier WR. Vergence accommodation and monocular closed loop blur accommodation have similar dynamic characteristics. *Vis Res*. 2007;47:327–337.
12. Thiagarajan P, Ciuffreda KJ. Visual fatigue and accommodative dynamics in asymptomatic individuals. *Optom Vis Sci*. 2013;90:57–65.
13. Campbell FW, Robson JG. High-speed infrared optometer. *J Opt Soc Am*. 1959;49:268.
14. Arnulf A, Dupuy O, Flamant F. Les microfluctuations d'accommodation de l'oeil. *Ann Opt Ocul*. 1955;3:109–118.
15. Pugh JR, Winn B. Modification of the Canon AutoRef R1 for use as a continuously recording infra-red optometer. *Ophthalmic Physiol Opt*. 1988;8:460–464.
16. Heron G, Winn B. Binocular accommodation reaction and response times for normal observers. *Ophthalmic Physiol Opt*. 1989;9:176–183.
17. Charman WN, Heron G. Fluctuations in accommodation: a review. *Ophthalmic Physiol Opt*. 1988;8:153–164.
18. Day M, Seidel D, Gray LS, Strang NC. The effect of modulating ocular depth of focus upon accommodation microfluctuations in myopic and emmetropic subjects. *Vis Res*. 2009;49:211–218.
19. Day M, Strang NC, Seidel D, Gray LS, Mallen EaH. Refractive group differences in accommodation microfluctuations with changing accommodation stimulus. *Ophthalmic Physiol Opt*. 2006;26:88–96.
20. Bergland G. A guided tour of the fast Fourier transform. *Spectr IEEE*. 1969;6:41–52.
21. Suryakumar R, Kwok D, Fernandez S, Bobier WR. Dynamic photorefraction system: an offline application for the dynamic analysis of ocular focus and pupil size from photorefraction images. *Comput Biol Med*. 2009;39:195–205.
22. Labhishetty V. *Calibration and Validation of the Dynamic Photorefraction System (DPRS)*. UWSpace: University of Waterloo; 2014.
23. Schaeffel F, Wilhelm H, Zrenner E. Inter-individual variability in the dynamics of natural accommodation in humans: relation to age and refractive errors. *J Physiol*. 1993;461:301–320.
24. Labhishetty V, Bobier WR. Are high lags of accommodation in myopic children due to motor deficits? *Vis Res*. 2017;130:9–21.
25. Bahill AT, Clark MR, Stark L. The main sequence, a tool for studying human eye movements. *Math Biosci*. 1975;24:191–204.
26. Alvarez TL, Semmlow JL, Yuan W, Munoz P. Dynamic details of disparity convergence eye movements. *Ann Biomed Eng*. 1999;27:380–390.
27. Blade PJ, Candy TR. Validation of the PowerRefractor for measuring human infant refraction. *Optom Vis Sci*. 2006;83:346–353.
28. Choi M, Weiss S, Schaeffel F, et al. Laboratory, clinical, and kindergarten test of a new eccentric infrared photorefractor (PowerRefractor). *Optom Vis Sci*. 2000;77:537–548.
29. Pugh JR, Eadie AS, Winn B, Heron G. Power spectrum analysis in the study of ocular mechanisms. *Ophthalmic Physiol Opt*. 1987;7:321–324.
30. Mordi JA, Ciuffreda KJ. Dynamic aspects of accommodation: age and presbyopia. *Vis Res*. 2004;44:591–601.
31. Suryakumar R. *Study of Dynamic Interactions Between Vergence and Accommodation (Appendix 1)*. University of Waterloo; 2005.
32. Kasthurirangan S, Vilupuru AS, Glasser A. Amplitude dependent accommodative dynamics in humans. *Vis Res*. 2003;43:2945–2956.
33. Anderson HA, Glasser A, Manny RE, Stuebing KK. Age-related changes in accommodative dynamics from preschool to adulthood. *Invest Ophthalmol Vis Sci*. 2010;51:614–622.