Effect of spatial filtering on accommodation

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ABSTRACT

The purpose of this study was to develop and test a new method that uses natural images to investigate the influence of their spatial frequency content on the accommodation response (AR). Furthermore, the minimum spatial frequency content was determined that was necessary to induce an AR. Blur of the images was manipulated digitally in the Fourier domain by filtering with a Sinc function. Fourteen young subjects participated in the experiment. A 2-step procedure was used: (1) verifying that a high amount of Sinc-blur does not evoke accommodation, (2) increasing the width of the Sinc-blur filter in logarithmic steps until an AR was evoked. AR was continuously monitored using eccentric infrared photorefraction at 60 Hz sampling rate under monocular viewing conditions. Under condition (1), Sinc-blur of $\lambda = 1$ cpd did not evoke accommodation, while under condition (2) an average (mean $\pm$ standard deviation) Sinc-blur of $\lambda = 5.57 \pm 4.67$ cpd (median: 4 cpd, interquartile range: 2–7 cpd) evoked accommodation. Dividing the subjects into myopes and emmetropes revealed that the myopic group required higher amounts of λ (higher spatial frequencies) to stimulate their accommodation (mean $\lambda = 9.33 \pm 4.99$ cpd, for myopes; and mean $\lambda = 2.75 \pm 0.97$ cpd, for emmetropes). Our results support the notion that the AR is most effectively stimulated at mid-spatial frequencies and that myopes may require higher spatial frequencies to elicit a comparable AR.

1. Introduction

Accommodation refers to the ability to produce changes in the power of the crystalline lens to obtain a focused image on the retinal plane for varying viewing distances (Charman, 2008). Since image blur is a visual signal with magnitude but no sign, the accommodative system requires additional cues to determine directional information, such as optical vergence (Del Águila-Carrasco et al., 2017), longitudinal chromatic aberration (Cholewiak, Love, & Banks, 2018), or microfluctuations of accommodation (Winn & Gilmartin, 1992). This concept has generated great controversy over the years, when studying blur as an accommodative stimulus, as it was assumed that the accommodative system uses a trial-and-error strategy (Phillips & Stark, 1977; Stark & Takahashi, 1965; Troelstra, Zuber, Miller, & Stark, 1964). First Fincham (1951) and later Smithline (1974) were the ones who introduced the idea that blur alone is not sufficient to stimulate accommodation and that secondary cues are necessary that contain information both on magnitude and direction (Cholewiak et al., 2018; Del Águila-Carrasco et al., 2017; Kruger & Pola, 1986; Kruger, Mathews, Aggarwala, & Sanchez, 1993; Kruger, Mathews, Aggarwala, Yager, & Kruger, 1995).

Generally, two kinds of stimuli have been assumed to stimulate accommodation: (1) Optical blur by the use of trial lenses and (2) Artificial blur, generated by manipulating the spatial frequency spectrum. The most common convolution was to digitally modify the slope of the spatial frequency amplitude spectrum (Vera-Diaz, Woods, & Peli, 2010; Webster, Georgeson, & Webster, 2002) or to use two dimensional Gaussian filters (Mather & Smith, 2002).

Image blur in the natural environment emerges from changes in accommodation or pupil size, which induce changes of the amplitude spectrum and systematic changes in the phase spectrum. Earlier computational approaches only generated changes in the amplitude spectrum but failed to mimic changes in the phase spectrum and are therefore not comparable with the natural sources of blur (Murray & Bex, 2010). As described by Murray and Bex (2010) the Sinc function is a digital image processing algorithm which attenuates the high spatial frequency components and also introduces periodic 180° reversals in phase that simulate optical blur more closely. Since both amplitude and phase spectrum determine the appearance of an image (Bex & Makous, 2002; Oppenheim & Lim, 1981) and are important for blur perception as well (Murray & Bex, 2010), the current study involved Sinc blur for studies on the accommodative response. Although dioptric blur is generally thought to be a low-pass filter, it should be noted that the use

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of low-pass digital filters for blur manipulation can produce qualitatively different images and reflect difficulties in order to introduce spurious resolution and other effects related to dioptric properties (Strasburger, Bach, & Heinrich, 2018).

Accommodation is not only determined by image blur but also spatial features of the accommodation target. Using sine-wave gratings with different spatial frequencies as accommodation targets, it was studied which spatial frequencies are particularly important. Some authors suggested that the accuracy of accommodation increases when the target contained spatial frequencies above 10 cycles per degree (cpd) (1978; Charman & Tucker, 1977; Heath, 1956; Tucker & Charman, 1987; Tucker, Charman, & Ward, 1986). However, other authors postulate that high spatial frequencies produce less stable ARs and that the mid-range spatial frequencies (2–5 cpd) are most important (Bour, 1981; Ciuffreda & Hokoda, 1983; Ciuffreda & Rumpf, 1985; Day, Gray, Seidel, & Strang, 2009; Raymond, Lindblad, & Leibowitz, 1984; Mathews & Kruger, 1994; Owens, 1980; Owens & Wolfe, 1985; Ward, 1987).

Another factor that might play a significant role in accommodation is foveal refractive error (Abbott, Schmid, & Strang, 1998; Charman, 1999; Gwiazda, Thorn, Bauer, & Held, 1993; Langaas et al., 2008). Several studies have investigated this issue but results are controversial (Day et al., 2009; Strang, Day, Gray, & Seidel, 2011; Taylor, Charman, O'Donnell, & Radhakrishnan, 2009; Xu, Zheng, Drobe, Jiang, & Chen, 2015). Most of them found no differences for the mean static accommodation behavior in myopes and emmetropes (Day et al., 2009; Taylor et al., 2009; Xu et al., 2015). However, Strang et al. (2011) observed that the accommodative response was dependent on both refractive error and spatial frequency content of the target. In most of the studies, Gabor patches with sine wave patterns with defined spatial frequencies were used. Spatially filtered natural images were not used. Therefore, the current study investigated the influence of spatial frequency spectra in the target images on the accommodative response. Furthermore, the lowest spatial frequencies were determined that still induced accommodation. In these experiments, the phases of the spatial frequency components were preserved by using the Sinc function for the digital filtering.

2. Material and methods

2.1. Participants

Fourteen young subjects with ages ranging from 20 to 29 years (mean age of 25.36 ± 2.35 years) and a mean spherical equivalent refractive error of -1.68 ± 1.62D were enrolled in the study (details are provided in Table 1). The following exclusion criteria applied:

Table 1
Age, gender, refraction and BCDVA (Best Corrected Distance Visual Acuity – LogMAR notation) of the subjects. Abbreviations: LE – Leading Eye, SE – Spherical Equivalent, OS – left eye, OD – right eye, F – female, M – male.

Subject	Gender	Age	LE	Sphere	Cylinder	Axis	SE	BCDVA
1	F	24	OD	−0.75	0.00	–	−0.75	−0.10
2	M	26	OD	−0.75	0.00	–	−0.75	−0.10
3	F	29	OD	−4.00	−0.25	174	−4.13	−0.10
4	M	23	OD	−4.75	−0.25	16	−4.88	−0.10
5	F	26	OS	−0.50	−0.25	19	−0.63	−0.10
6	F	24	OS	−3.25	−1.25	172	−3.88	−0.10
7	M	26	OD	−0.25	−0.50	108	−0.50	−0.10
8	F	26	OD	−2.25	−0.25	171	−2.38	−0.10
9	M	24	OD	0.50	0.00	–	0.50	−0.10
10	M	20	OD	−0.75	0.00	–	−0.75	−0.10
11	M	24	OS	0.00	−0.25	94	−0.13	−0.10
12	M	26	OS	−1.75	−0.5	159	−2.00	−0.10
13	M	28	OD	−2.50	−0.75	162	−2.88	−0.10
14	F	29	OS	−0.25	−0.50	17	−0.50	0.00

myopia exceeding 6.0D, astigmatism exceeding 2.0D, known ocular pathologies, accommodation disorders or simultaneous participation in clinical trials.

The study was in accordance with the tenets of the declaration of Helsinki of 1964 and was approved by the Ethics Commission of the University of Tübingen. Signed informed consent was obtained from each subject after the study was explained in detail.

2.2. Optometric examination and calibration of the photorefractor

Objective refractions were performed using a wavefront aberrometer (i.Profiler®plus, Carl Zeiss Vision GmbH, Aalen, Germany). Subjective refractions were determined using a digital phoropter (ZEISS Visuphor 500®, Carl Zeiss Vision GmbH, Aalen, Germany). Best corrected distance visual acuity (BCDVA) was measured with the maximum plus correction to obtain maximum visual acuity (MPMVA). The dominant (leading) eye was determined using the Dolman method (also called the hole-in-the-card test; Cheng, Yen, Lin, Hsia, & Hsu, 2004). Myopia was defined as spherical equivalent < -0.75D, emmetropia as ≥ -0.75D to $+0.75$D and hyperopia as $> +0.75$D. Only data from the leading eye were used.

Individual calibration of the eccentric photorefractor was required to optimize its accuracy and to reduce measurement below 0.25D (Schaeffel, Wilhelm, & Zrenner, 1993; Seidemann & Schaeffel, 2003; Wagner, Ohlendorf, Schaeffel, & Wahl, 2016). In eccentric photorefraction, refractive errors (in D) are calculated by multiplying the luminance slope in the pupil with a constant that varies among different individuals by about 10 percent. Refractions are mostly reliable in the middle of the dynamic range of the 8bit monochrome camera at pixel gray levels between 90 and 140. In this range, pixel grey levels are linearly related to luminances and the steepness of the luminance profiles in the pupil are correctly measured. This was considered for data filtering, and all data outside this range were removed.

2.3. Accommodation stimuli

A natural image showing foliage and plants with a resolution of 3120×4160 pixels served as visual stimulus for the experiments (Fig. 1). The amplitude of spatial frequency components in the image declined with increasing spatial frequencies with the reciprocal of the spatial frequency, as described by Field (1987). The image was converted to grayscale, cropped, and resized to subtend a visual angle of 4° at a viewing distance of 50 cm.

To avoid that the edges of the image could serve as an accommodation cue they were smoothened using a Sinc window (as defined in Eq. (1)). Sizes of Sinc windows (before the first oscillation occurred) and the image used as accommodation target were matched. In the center, the amplitude of the Sinc window was 1. Towards the periphery, amplitude decreased and approached zero at the borders of the image. Subsequent image processing was based on the blur manipulation in the Fourier domain. It was accomplished using a Sinc function (Eq. (1), where λ is correlated with the blur level and determined the spatial frequency (ω) at which the phase first turns back) (Murray & Bex, 2010).

$$A(w) = \frac{\sin\left(\frac{\pi w}{\lambda}\right)}{\frac{\pi w}{\lambda}} \tag{1}$$

The final images were adjusted to match the same mean root mean square contrast and mean luminance as the original, using Eq. (2) (Vera-Diaz et al., 2010; Webster et al., 2002), where I is the original image, M∆s is the filtered image and P∆s is the final altered image. The contrast was adjusted at each pixel of the filtered image [M∆s(x,y)] and consequently, the mean and standard deviation (std) of each pixel were the same as in the original image. This adjustment prevented subjects from using image contrast as a cue to distinguish between the different
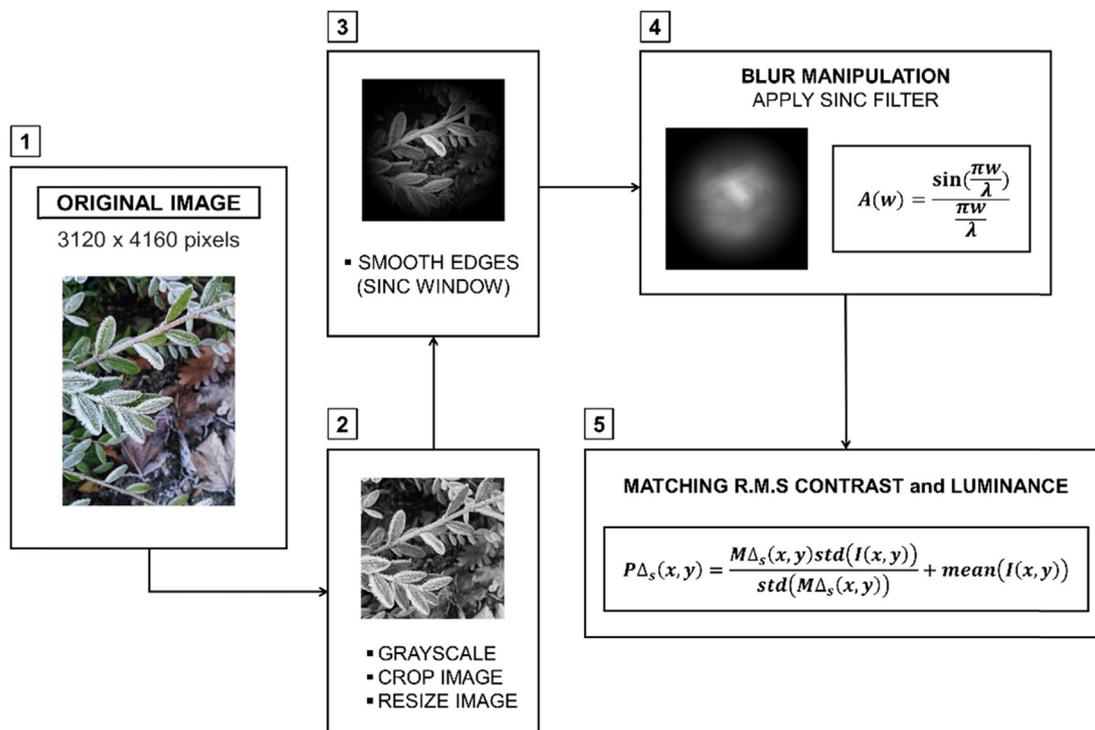
Fig. 1. Steps involved in the image processing to generate the accommodation target. (1) Original image with a resolution of 3120 × 4160 pixels; (2) Manipulation of original image properties (size and color); (3) Application of the Sinc window to blur the borders of the image; (4) Blur manipulation in the Fourier domain; (5) Adjustment of R.M.S contrast and luminance between modified and original images.

levels of sharpness or blur, as described by Vera-Diaz et al. (2010).

$$P\Delta_s(x, y) = \frac{M\Delta_s(x, y)std(I(x, y))}{std(M\Delta_s(x, y))} + mean(I(x, y)) \qquad (2)$$

2.4. Experimental setup

The experimental set-up consisted of a liquid crystal display (LCD) positioned at a fixed distance of 50 cm from the subject to induce an accommodation demand of 2D. The fixation axis of the dominant eye was aligned with the camera axis of the eccentric infrared photo-refractor to minimize interference with vergence. The photorefractor was positioned at 1 m distance from the subject. An infrared photo-retinoscope, a camera DMK 23UM021 (TheImagingSource, Germany), and a Cosmica Pentax 50 mm lens was used as previously described (Seidemann & Schaeffel, 2003). Sampling was at 60 Hz. The LCD monitor was a 10.1 in. display with a screen resolution of 1920 × 1200 pixels, an aspect ratio of 16:9 and a screen refresh rate of 60 Hz. Minimum angle of resolution was equivalent to −0.2logMAR. The visual stimulus, presented in the middle of the LCD monitor subtended a vertical and horizontal visual angle of 4°. Prior to the analysis of the accommodation data, data filtering was required in order to reduce the number of outliers. Sources for outliers were eyelid blinks or partially covered pupils by the eye lids. Data inside the middle of the dynamic range of the 8bit cameras (between 90 and 140) and pupil sizes that were within the range of ± 0.1 standard deviations were included in the final analysis. The mean luminance was 4.69 ± 0.08 cd/m^2 for minimum λ and 4.63 ± 0.07 cd/m^2 for maximum λ, using a neutral density filter (1.2 ND filter, LEE Filters, United Kingdom). Room illuminance was approximately 1 lx at the eye level of the subject.

2.5. Experimental procedure

A two-step procedure (Fig. 2) was followed:
During Phase (1), it was verified that Sinc-blur filtered images

(λ = 1 cpd) did not drive the AR, even when trial lenses of different spherical powers (−4 to +1 in steps of 1 D) were placed in front of the eye. The exchange of the lenses was done manually with a time interval of 5 s for each lens. Specifically, this phase aimed to observe whether the stimulus itself could drive accommodation and therefore no accommodation response would be evoked when the stimulus was defocused by trial lenses.

In Phase (2) of the experiment, the λ of the Sinc-blur filter was increased in logarithmic steps until an increase in the AR was detectable. The threshold for a significant change in accommodation was set at an average value of 0.3D because this value matches the depth of focus of the human eye (Campbell, 1957) and because it represents a clinically significant change in accommodation (Wagner et al., 2016). Furthermore, its represents the dioptric range of microfluctuations of accommodation and is slightly above than the noise range of infrared photorefraction (Schaeffel et al., 1993). Lambda was increased in steps from 0.5 to 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024 cpd, generating maximum to minimum blur. The AR was continuously recorded for 3 s under each condition.

2.6. Statistics

Statistical analysis was carried out using the SPSS statistical software (version 22.0). Normality of the data was verified by the Kolmogorov-Smirnov test. Student's *t*-test for paired data was applied when there was a normal distribution of the data. Wilcoxon-signed rank test was used when nonparametric analysis was required. An additional analysis was added to compare differences among accommodative responses when lenses of different power were placed in front of the eye. Analysis of Variance (ANOVA) or Kruskal-Wallis tests were used, depending on the distribution of the data. The Bonferroni's or Mann-Whitney's adjustment was used for the post-hoc comparative analyses. Differences were considered statistically significant when the associated P value was lower than 0.05. Results are provided as mean ± standard deviation.
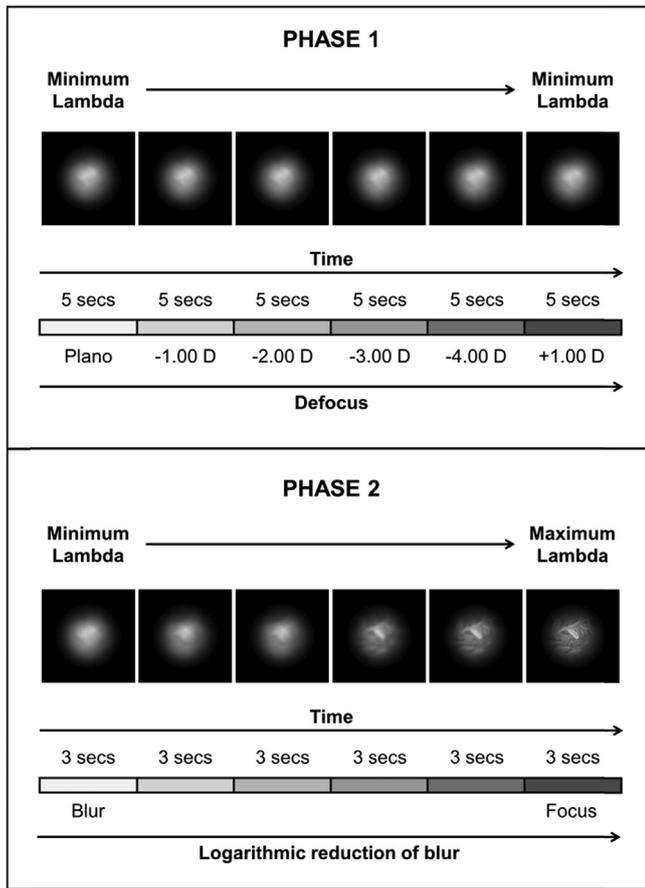
Fig. 2. Strategy of the experimental paradigm (2-step process). The accommodative response was measured continuously as the subjects looked at the visual target (minimum λ = maximum blur) while trial lenses of different powers (−4 to +1 in steps of 1 D) were positioned in front of the examined eye (Phase 1); and during the logarithmic increase of the magnitude of λ (logarithmic reduction of the visual stimulus blur).

3. Results

3.1. Phase (1) – the AR with high amounts of target blur

Means and standard deviations of the ARs were calculated for each accommodation demand, while the subject looked at the image, with a Sinc blur of λ = 1 cpd. It was verified that no accommodation response was induced when trial lenses were placed in front of the eye (−4D to +1D). If no sign of accommodation was detected it could be concluded that the target was digitally sufficiently low-pass filtered to remove cues from defocus imposed by the lenses. No significant differences were found in the mean AR ($\chi^2(2) = 0.086$, p > 0.05, Kruskal-Wallis test) among all the intervals, no matter which lens was placed in front of the eye (see Fig. 3).

3.2. Phase (2) – individual levels of Sinc-blur

Taking into account the depth of focus of the human eye (Campbell, 1957), the microfluctuations of the accommodative system (0.20D, Stark & Atchison, 1997) and instrumental errors (after calibration: 0.25D or less, Schaeffel et al., 1993), a shift in myopic direction by 0.30D was set as threshold for the change in the accommodative response, when the λ of the target was increased in logarithmic steps. Individual amounts of Sinc-blur were explored for all subjects and clear inter-individual differences were found. To elicit accommodation, a mean λ of 5.57 ± 4.67 cpd was necessary (median: 4 cpd, interquartile range: 2–7 cpd). Analyzing individually the relationship between the SE
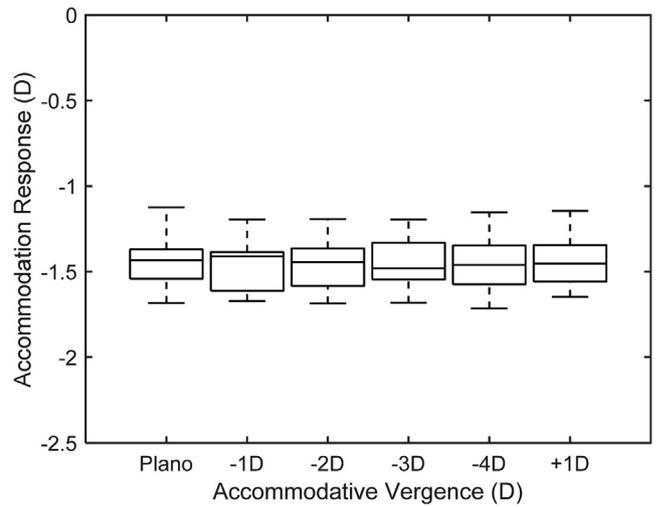

Fig. 3. Averages of measured refractions in all subjects, when the image that served as accommodation target was severely blurred (λ = 1 cpd). The y-axis represents the average of the accommodative response in diopters and the x-axis represents each of the accommodative demands used during Phase (1). Error bars denote standard deviations.
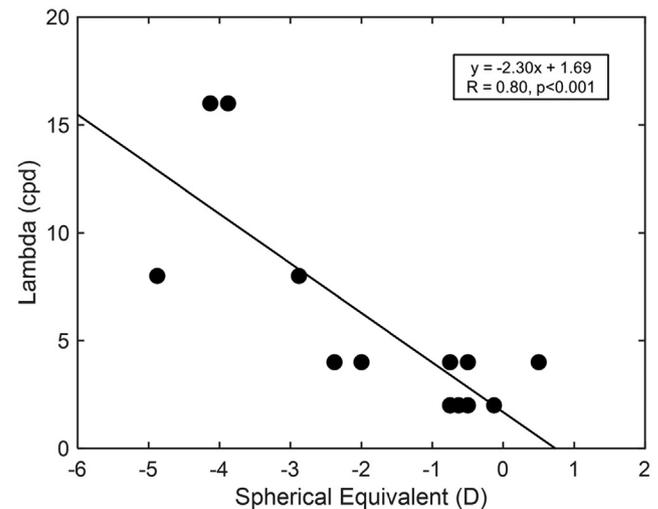

Fig. 4. Scatterplot indicating the relationship between spherical refraction vs individual lambda calculated in Phase (2). There was a negative significant correlation between both variables (Pearson correlation coefficient = −0.80; covariance = −6.50; p < 0.001).

and lambda calculated in Phase (2) revealed a significant negative correlation (Pearson correlation coefficient = −0.80; covariance = −6.50; p < 0.01) (Fig. 4).

Fig. 5 shows the mean AR for different λ for the different refractive groups. Compared to the Sinc-blur λ = 1 cpd (λ level number 2), a significant increase in accommodation was observed in the subjects ($\chi^2(2) = 708.49$ and $\chi^2(2) = 719.92$, p < 0.001, Kruskal-Wallis test; emmetropes and myopes, respectively). After reaching the best level of λ, an increase in the spatial frequency of the accommodation stimulus did not produce any further increase in the AR, when compared to the results obtained in the mid-range spatial frequencies for both refractive groups ($\chi^2(2) = 0.18$ and $\chi^2(2) = 1.10$, p > 0.10, Kruskal-Wallis test; emmetropes and myopes, respectively). These results suggested that mid-range spatial frequencies were most important for stable AR in all of the subjects.
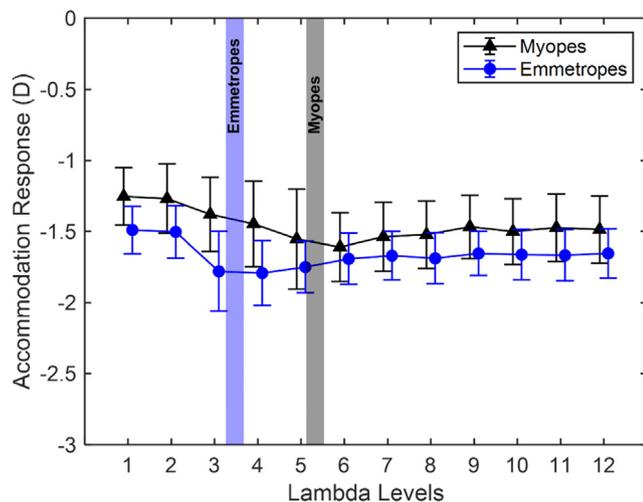
Fig. 5. Mean accommodative responses during Phase (2) of the experiment depending on the central refractive error and the level of λ. Y-axis represents the accommodative response in diopters, and blur levels (λ) of the visual stimulus are presented on the x-axis. Error bars are standard deviations. Black lines represent myopes and blue lines emmetropes. Blue and grey shaded stripes represent the average zone where the AR exceeded for the first time the threshold of 0.3D in the emmetropic and myopic groups, respectively. The twelve levels of λ were equivalent to: 0.5, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024 cpd. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. Differences between myopes and emmetropes

Dividing subjects into myopes (mean spherical equivalent = −3.36 ± 1.02D; n = 6) and emmetropes (mean spherical equivalent = −0.44 ± 0.40D; n = 8) revealed that myopes required higher amounts of λ (lower levels of Sinc-blur) to stimulate their accommodative system in comparison with emmetropes (mean λ = 9.33 ± 4.99 cpd, median: 8 cpd, interquartile range: 5–14 cpd, for myopes; and mean λ = 2.75 ± 0.97 cpd, median: 2 cpd, interquartile range: 2–4 cpd, for emmetropes). The differences between both groups were significant (Z = −2.220, p = 0.02, Wilcoxon-signed rank test), confirming that myopes were less responsive to Sinc-blur than emmetropes.

4. Discussion

Using digital blur of a natural image, we have analyzed the required spatial frequencies necessary to stimulate the human AR. The three major findings were: (1) a Sinc-blur spatial frequency of λ = 1 cpd does not evoke accommodation, (2) the mean required level of λ to stimulate accommodation was λ = 5.57 ± 4.67 cpd and (3) myopes required higher levels of λ for stimulation of the accommodative response, compared to emmetropes.

4.1. Target spatial frequency and the response of the accommodation system

Using Gabor targets as a visual stimulus, different authors have investigated the performance of the accommodative system as a function of the spatial frequencies of the stimulus. Two opposing viewpoints have emerged from this type of research: (1) high spatial frequencies are required for accurate accommodation, or (2) mid spatial frequencies are sufficient to elicit an accurate AR. Phase (1) of our experiment showed that the use of Sinc-blur filtering at λ = 1 cpd completely suppressed the ARs and defocus imposed by trial lenses had no effect. In phase (2), higher spatial frequency contributions were stepwise elevated until an optimal response of the AR was elicited. Starting from a

low spatial frequency target (λ = 0.5 cpd), target details needed to be added to stimulate accommodation. The required levels of Sinc-blur to reach an accurate response varied among subjects and the average level needed was λ = 5.57 ± 4.67 cpd (median: 4 cpd, interquartile range: 2–7 cpd). One effect that may have influenced these results was that the subjects adapted during the experiment due to the fact that Sinc blur was not presented in a randomized order. Adaptation could therefore have occurred only to the lower spatial frequencies but not to the higher spatial frequencies than were added step by step.

It was interesting that accommodation did not further increase when higher spatial frequencies were added. This corroborates previous conclusions that mid-range spatial frequencies are most important to drive accommodation (Bour, 1981; Ciuffreda & Hokoda, 1983; Ciuffreda & Rumpf, 1985; Esteve-Taboada, Bernal-Molina, Montés-Micó, & Ferrer-Blasco, 2018; Owens & Wolfe, 1985; Owens, 1980; Raymond et al., 1984; Ward, 1987). Using sine wave gratings, Owens (1980) was one of the first to show the importance of intermediate spatial frequencies. Later, Owens and Wolfe (1985) showed that accommodation was better at 4.2 cpd, compared to 1.0 and 6.5 cpd. Ward (1987) observed that accommodation was less stable at 15 cpd. Charman and Tucker (1977) reported unstable steady-state monocular accommodation for sinusoidal grating targets at low spatial frequencies (< 5 cpd) and also found that accuracy improved with higher grating frequency. Furthermore, they observed that the eye returned to the resting point of accommodation when only low spatial frequencies (< 1 cpd) were provided. They also showed difficulties to elicit an adequate accommodation response when high spatial frequency pattern was presented (≥ 30 cpd). More recently, Esteve-Taboada et al. (2018) also confirmed that the AR was most accurate at intermediate spatial frequencies (< 15 cpd).

4.2. Differences between myopes and emmetropes in the AR under the effect of spatial frequencies

We found that myopic subjects required higher spatial frequency components in the visual target for stimulation of their accommodation (mean λ = 9.33 ± 4.99 cpd, median: 8 cpd, interquartile range: 5–14 cpd). Emmetropes were able to accommodate with less details in the target image (mean λ = 2.75 ± 0.97 cpd, median: 2 cpd, interquartile range: 2–4 cpd) as shown in Fig. 5. The effect of refractive error has been studied previously but the results varied. Day et al. (2009) could not find changes in static accommodation, neither with spatial frequency of sine or square wave targets (0.5, 1, 2, 4, 8, 16 cpd) nor with refractive errors. Taylor et al. (2009) observed similar mean static accommodation in myopes and emmetropes using Gabor targets with spatial frequencies of 1, 4, 8 and 16 cpd. In contrast, Strang et al. (2011) found that emmetropes accommodated more for sine wave gratings of 4 cpd, compared to 0.5 cpd and 16 cpd, while myopes accommodated more for both 4 cpd and 0.5 cpd, compared to 16 cpd.

Our results revealed obvious differences in the processing of blur between myopes and non-myopes. Possible mechanisms could be that myopes who are almost always somewhat under corrected are continuously adapted to some level of blur and are therefore less sensitive to changes in contrast at higher spatial frequencies. It could also be that myopia itself includes changes in retinal processing of contrast at higher spatial frequencies. Less sensitivity to the presence of blur may lead that the accommodative system is unable to appreciate the increase in the low-mid spatial frequency range of the visual stimulus. It has also been proposed that reduced blur sensitivity may trigger axial eye growth as it may be producing a hyperopic retinal defocus due to a reduced AR (Rosenfield & Abraham-Cohen, 1999; Schaeffel, Glasser, & Howland, 1988). Despite the significance of the results and the observed trends, certain other aspects need to be considered. First, the non-homogeneity and small sample size in each refractive group may have led to variation in the results. Second, the refractive error threshold may have been overestimated and therefore certain

emmetropes may be placed in the myopic group. However, these subjects did not require the use of correction in their daily life to achieve significant improvements in their visual conditions. Third, a Sinc-blur filter was used to manipulate the image. However digital manipulation of blur and contrast may obviate other possible aspects that could incorporate depth-dependent effects and therefore be necessary for the accommodation response, such as longitudinal chromatic aberration, astigmatism and spherical aberration (Cholewiak et al., 2018). In addition, the use of low-pass digital filters for blur manipulation may reflect difficulties in introducing spurious resolution and other effects related to dioptric properties that may impact accommodative response.

4.3. Implications on myopia research

There is evidence that accommodation performance is correlated with the onset and progression of myopia (Abbott et al., 1998; Charman, 1999; Gwiazda et al., 1993; Langaas et al., 2008). The current study shown that a certain range of spatial frequencies must be available in natural images to induce accurate accommodation. The approach used may be useful for future studies on the link between reading, accommodation and the onset or the development of myopia. Additionally, training procedures could be developed (i.e. Wagner et al., 2016) to improve the accuracy of the accommodation in myopes to reduce their retinal focus error signal during near work.

5. Conclusion

In this study, digital spatial filtering of natural images was performed to describe the effect of spatial frequency content on the AR. Furthermore, minimum spatial frequencies were determined that were necessary to produce accommodation. Our study provides further evidence that the mid-range spatial frequency spectrum is most important. To improve accommodation, future studies could perhaps also optimize the mid spatial frequency content of a target.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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