Title:

Effect of apparent depth cues on accommodation in a Badal optometer.

Running title:

Apparent depth cues on accommodation.

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Background: To analyze the effect of peripheral depth cues on accommodation in Badal optometers.

Methods: Monocular refractions at 0.17 and 5.00 D of Accommodation Stimulation (AS) were measured with the PowerRef II autorefractor (Plusoptix Inc., USA). Subjects looked (randomly) at 4 different scenes: one real scene comprising familiar objects at different depth planes (Real); and three virtual scenes comprising different 2-dimensional pictures seen through a Badal lens. The first image consisted of a photograph of the real scene taken in conditions that closely mimic a healthy standard human eye performance (Out-of-Focus (OoF) blur); the second image was the same photograph rendered with a depth of focus to infinity (Out-of-Focus sharpness); and finally the third image consisted of a fixation target and a white even surrounding (White). In all cases the field of view was 25.0º and the fixation target was a Maltese cross subtending to 2º.

Results: 28 right eyes from healthy young subjects were measured. The achieved statistical power was 0.9. At 5 D of AS, the repeated measures ANOVA was statistically significant ($p<0.05$) and the corresponding Bonferroni post-hoc tests showed the following mean Accommodation Response (AR) differences ± SD (p-value) between the real and the virtual scenes: real-white=-0.66 D ± 0.92 D ($p<0.01$); real-OoF sharpness=-0.43 ± 0.88 D ($p=0.07$); real-OoF blur=-0.25 ± 0.93 D ($p=0.89$).

Conclusions: A stimulus poor in depth cues inaccurately stimulates accommodation in Badal optometers. However, accommodation can be significantly improved in the same Badal optometer when displaying a realistic image rich in peripheral depth cues, even though these peripheral cues (also referred to as retinal blur cues) are shown in the same plane as the fixation target. These results have important implications in stereoscopic virtual reality systems that fail to represent retinal blur appropriately.

Keywords: Accommodation, Badal optometer, apparent depth, simulated blur.

In a previous study the closed-loop, steady-state accommodation response (AR) to a Badal optometer was found significantly inaccurate when compared to real space targets.[1] Contributing factors of the Badal lens that could explain the differences are the field of view (FOV), the instrument's cover proximity, the angular size of the stimulus and the peripheral interposition of objects in depth. However, only the interposition of objects in depth significantly affected the response to accommodation, suggesting that a peripheral surround at a different distance than the fixation target might provide an important cue for appropriate accommodation.[2]

Usually the accommodative stimulus in Badal optometers comprise only a fixation target (for instance, a Maltese cross) on an even background in a 2-dimensional surface.[3–5] In the context of a specific FOV, an important difference between this configuration and natural viewing conditions is the lack of peripheral depth cues. Two methods can be used to address this dissimilarity. On the one hand, a volumetric (multiplane display) Badal optometer[6] has been recently developed for stereoscopic virtual reality applications. This novel system creates multiple focal planes that theoretically allow real depth representation of objects and thus a 3-D reconstruction of scenes.[7] In these systems the contents of scenes that are in different planes than the fixation target are defocused relatively to the fixation plane. The out-of-focus contents of a scene is optically blurred, i.e., blur arises from the optics of the observer's eye similarly to what occurs in natural viewing conditions. However, these systems are generally difficult to implement and significant technological limitations exist in the number of focal planes that can be displayed.[8,9] In consequence, they are still only used for research purposes. A

Badal optometer with a 2-dimensional stimulus comprising apparent depth cues that include rendered out-of-focus blur presents an alternative to volumetric systems. Apparent depth cues influence accommodation in closed-loop conditions. Busby et al.[10] analyzed the effect of pictorial images on 3 D of accommodation stimulation and found mean differences of 0.28 D between two positions of a picture with different apparent depth perceptions. Similarly, Takeda et al.[11,12] found mean accommodative differences of 0.68 D (for 4 D of AS)[12] and even 0.77 D (for 3 D of AS).[11] In addition, rendered out-of-focus blur may enhance depth perception,[13–15] with a potential effect also on accommodation.

To our knowledge, the concepts of apparent depth and rendered out-of-focus blur have not been studied in the context of objective measurements of accommodation stimulated with a Badal optometer. A better understanding of the role of these concepts on the AR may lead to improved lens-based methods to stimulate accommodation in virtual reality. The purpose of this study is to investigate the stimulation of accommodation in a Badal optometer when a 2-dimensional stimulus with apparent depth cues that include rendered out-of-focus blur is used.

METHODS

Subjects

The study was approved by the Ethics Committee of Hospital Mutua de Terrassa (Terrassa, Spain). It followed the tenets of the Declaration of Helsinki and all subjects gave informed written consent. Criteria for inclusion were best corrected visual acuity of 0.10 logMAR or better and no history of any ocular condition, surgery and/or pharmacological treatment. Only one eye of each subject was included in the analysis and corrected with spherical and cylindrical components of over-refractions within ±0.25 D. The upper age limit was set at 27 years to ensure good amplitude of accommodation. Mean age ± standard deviation of 28 subjects were 24.6 ± 2.4 years (20 to 27 years) with mean corrected logMAR visual acuity of –0.10 ± 0.08 (–0.20 to +0.10) and mean subjective amplitude of accommodation of 11.8 ± 2.0 D (8.3 to 16.6 D).

Instrumentation and setup

The binocular open field autorefractor PowerRef II (Plusoptix Inc., USA) was used in all measurements. It is based on dynamic infrared retinoscopy and it measures the spherical equivalent, pupil size and gaze position at a sampling frequency of 25 Hz.[16] Alignment between the PowerRef II and the patient's eye was achieved by means of a 50-mm squared Hot Mirror (reflects IR, transmits visible) placed 25 mm from the patient's pupil plane (Figure 1).

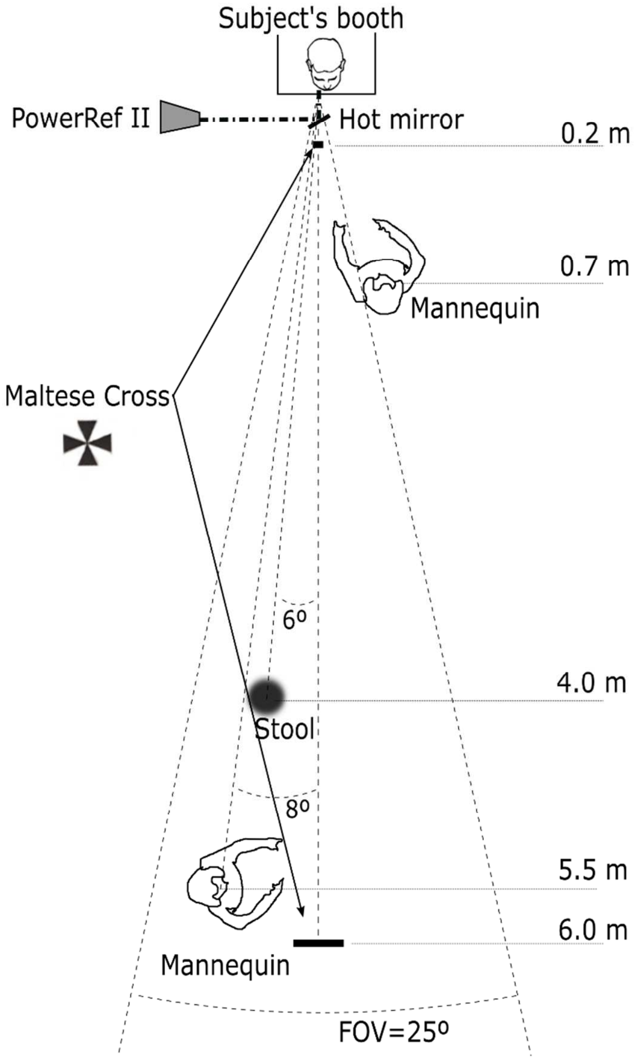

Figure 1. Top-view of the real 3-dimensional space setup (Configuration 1). Distances are shown in meters (m) in relation to the eye's pupil plane.

The setup consisted of the PowerRef II autorefractometer and different configurations to stimulate accommodation. Autorefractometer measurements were taken at target distances of 6 m and 20 cm or equivalent positions in a Badal system, corresponding to accommodation stimuli of 0.17 D and 5.0 D, respectively. In all cases, luminance of the stimulus was constant (white region: 54 cd/m^2; black region: 2.33 cd/m^2), the field of view of the scene was limited to 25.0º and the fixation target was a black Maltese cross subtending 2.0º.

The *first configuration* consisted of stimulating accommodation with free 3-dimensional space targets. The scene displayed included the fixation target; it was also designed to provide some peripheral depth cues at different focal planes, including three well-known objects: two mannequins of the same height at a distance of 5.5 and 0.7 meters, respectively, and a stool at a distance of 4 meters (Figure 1) in relation to the eye's pupil plane. In this study, this configuration is the closest to natural viewing conditions. However, in the present study subjects were accommodating monocularly, with the other eye occluded, whereas binocular viewing, which includes cues such as vergence and disparity that are missing in monocular conditions, is more appropriately referred to as "natural viewing".

The *second configuration* consisted of a Badal optometer (Badal lens f'=100 mm, diameter=49 mm). The stimulus was a photograph of the real scene shown in the first configuration for each AS. These pictures were taken to closely approximate human sight. As shown in Figures 2a and 2b, each photograph focused on the Maltese cross plane and therefore the remaining contents of the scene appears blurred in relation to the relative distance to the Maltese cross plane.

The *third configuration* consisted of the same previous Badal optometer, but using only the photograph taken at far distance for all accommodative stimulations. In this case, the photograph was computationally rendered with an infinite depth of focus and thus the whole scene looked sharp, even those objects that in the real scene were at different focal planes from the fixation target (figure 2c, 2d).

The *fourth configuration* consisted of the same previous Badal optometer with a black Maltese cross on a white even surrounding (Figure 2e, 2f), a configuration often used in accommodation studies.[4,5,17,18] A summary of each configuration can be found in table 1.

Table 1. Summary of the 4 setup configurations. SM: Stimulation Method, FOV: Field Of View, OoFB: Out-of-Focus Blur, AS: Accommodation Stimulation.

Config.	SM	FOV [º]	Scene (label)	OoFB	AS
1	Real target	25	Real (Real)	Yes	0.17 & 5.00 D
2	Badal target	25	Picture of the real scene (OoF Blur)	Yes	0.17 & 5.00 D
3	Badal target	25	Picture of the real scene rendered with DOF to infinity (OoF Sharpness)	No	0.17 & 5.00 D
4	Badal target	25	White uniform background (White)	No	0.17 & 5.00 D

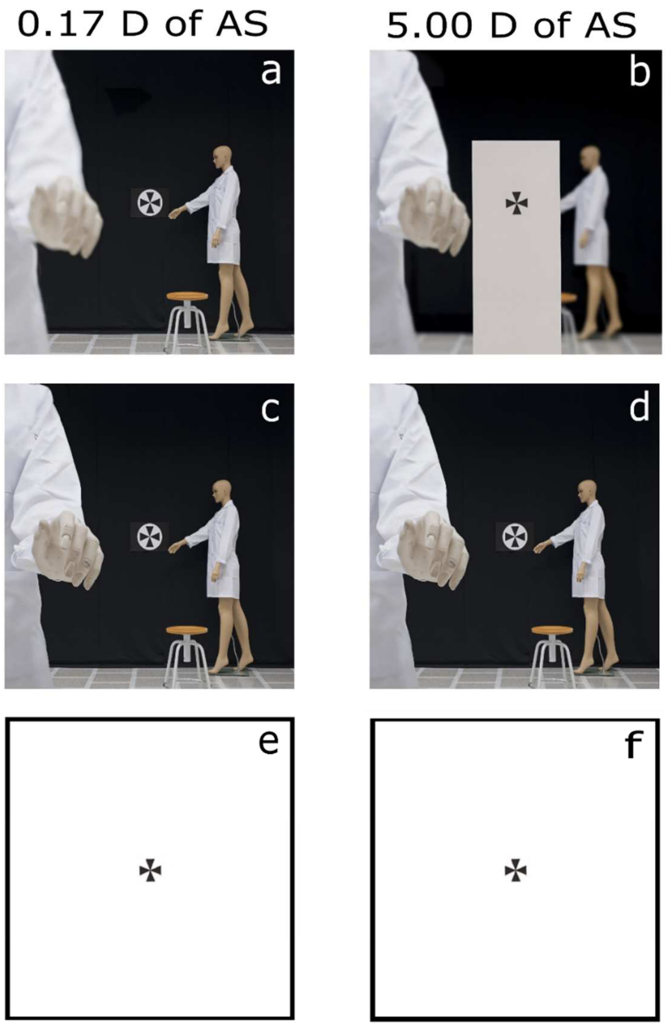

Figure 2. Accommodative stimulus used at 0.17 D (a, c, e) and 5.00 D (b, d, f) in the Badal optometer. Configuration 2 (a, b), Configuration 3 (c, d) and Configuration 4 (e, f).

Characteristics of the Photographs

All images were taken with a Nikon D700 camera and a 60-mm Micro Nikkor lens (Nikkon Inc., Japan). The same light source of the real scene was used to illuminate the photographs, adjusting the white balance of the camera to the corresponding color temperature. Once the images were captured, they were processed with a luminance transition curve akin to that of the human vision.[19]

In the second configuration, a depth of focus (DoF) of ±0.30 D was considered to obtain a picture with a DoF similar to a healthy human subject under standard room lighting conditions (500 lux).[20] The camera's f-number used was f/8. This configuration is potentially limited since depth of focus is variable across subjects and its inter-subject variability can be affected by the accommodative demand.[21]

For the third configuration, the image with an infinite depth of focus was captured with the same equipment and settings as the images of the second configuration. The infinite depth of focus was obtained using image-processing techniques. Several images at different focal planes were captured. Magnifications were unified and stacked with the focus-stacking tool of Adobe Photoshop CS4 (Adobe Systems Inc., USA).

Finally, all images were printed using a sublimation printing system with a resolution of 5 lp/mm (line pairs per millimeter) that is shown to elicit accurate accommodation.[22]

Examination Protocol

Firstly, an optometric examination was performed. Monocular subjective refraction was measured with the endpoint criteria of maximum plus power consistent with best vision. The eye with best visual acuity was chosen for the measurements and the push-up method provided the monocular amplitude of accommodation.

Next, subjects were blindfolded and moved to the measurement room. During all measurements they remained inside a booth and were not aware of the real dimensions of the setup nor the room to avoid biases in the accommodative response.[2] Once the participants sat in front of the chin rest, they remained blindfolded for another 5 minutes to ensure that all started from the same baseline accommodative level (wash-out accommodation procedure).[2] Afterwards, the spherical equivalent refraction was measured in one eye (the contralateral eye was occluded) for the previously described configurations and in ascending level of accommodative stimulation (0.17 D and 5.00 D) to minimize difficulties in relaxing the accommodation. The subjects were instructed to look at the centre of the cross and carefully focus it. The four configurations were randomized and the spherical equivalent of the eye was recorded over a period of 5 seconds in each case. The accommodation responses for the 5.00 D stimulus were determined by subtracting the refractions for the 0.17 D stimulus from the refractions for the 5.00 stimulus. The resulting accommodation response was negative in order to be consistent with refraction.

Statistical analysis

The significance was set at 0.05 and the statistical analysis was performed using SPSS v22 (IBM Corp., USA). Normality of each variable was verified with the Shapiro-Wilk test and comparing skewness and kurtosis to the standard error. The repeated measures ANOVA was used to analyze within-participant effects (i.e., the overall significant difference between each configuration). When significance was obtained, pairwise comparisons were examined by t-tests with the Bonferroni correction. In addition, to further assess individual differences in the accommodative ability of observers, regression and correlation coefficients are also provided.

RESULTS

The post hoc power analysis carried out with the open source G*Power 3.0.10 showed a mean power effect of 0.9 for a sample size of 30 subjects.

The descriptive statistics (mean, standard deviation and within-subject standard deviation) of far refraction (AS at 0.17 D), refraction at 5.00 D of AS and accommodative response at 5.00 D of AS are shown in Table 2 for each configuration. The descriptive statistics of pupil size and gaze position (with respect to the optical axis of the PowerRef II) are also shown.

The repeated measures ANOVA for far refraction was not statistically significant ($F_{3.0,\ 87.0}$=2.00 and p=0.12); in contrast, ANOVA was significant for refraction ($F_{3.0,\ 87.0}$=6.40 and p<0.01) and accommodative response at 5.00 D of AS ($F_{3.0,\ 87.0}$=5.24 and p<0.01). The pairwise comparisons between configurations are shown in Figure 3.

The pupil size differences among configurations were not statistically significant in any case: $F_{3.0,\ 87.0}$=1.12 and p=0.35 for stimulus at 0.17 D and $F_{2.3,\ 61.6}$=3.98 and p=0.02 for stimulus at 5.00 D (the Bonferroni post-hoc test did not show statistical significance). Similarly, the gaze position was not significantly different among configurations: $F_{2.1,\ 64.0}$=0.45 and p=0.64 for stimulus at 0.17 D and $F_{2.2,\ 68.6}$=0.91 and p=0.41 for stimulus at 5.00 D.

Table 2. Descriptive statistics of the far distance measurements, near distance measurements and the Accommodative Response (AR) at 5.00 D in all configurations. SE: Spherical Equivalent in diopters. PS: Pupil Size in millimeters. GP: Gaze Position in degrees. SD: Standard deviation. Sw: Within-subject standard deviation.

	Stimulus at 0.17 D			Stimulus at 5.00 D			AR at 5 D
Config.	Mean SE ± SD (Sw)	Mean PS ± SD (Sw)	Mean GP ± SD (Sw)	Mean SE ± SD (Sw)	Mean PS ± SD (Sw)	Mean GP ± SD (Sw)	Mean SE ± SD (Sw)
Real (1)	0.15 ± 0.81 (0.17)	5.38 ± 1.12 (0.29)	2.96 ± 1.87 (1.61)	-3.61 ± 1.03 (0.39)	4.67 ± 0.92 (0.28)	4.64 ± 3.47 (2.35)	-3.76 ± 0.96 (0.43)
OoF blur (2)	0.00 ± 0.82 (0.13)	5.60 ± 0.94 (0.25)	3.30 ± 1.89 (1.57)	-3.51 ± 0.90 (0.28)	4.96 ± 1.04 (0.32)	4.23 ± 2.51 (2.65)	-3.51 ± 1.08 (0.31)
OoF sharpness (3)	-0.09 ± 1.00 (0.16)	5.47 ± 1.08 (0.29)	3.07 ± 1.99 (1.60)	-3.42 ± 0.92 (0.47)	4.97 ± 1.00 (0.28)	4.78 ± 2.94 (2.44)	-3.33 ± 1.01 (0.49)
White (4)	0.05 ± 0.76 (0.27)	5.74 ± 0.98 (0.29)	3.31 ± 2.40 (1.75)	-3.06 ± 1.05 (0.53)	4.67 ± 1.01 (0.33)	4.19 ± 2.55 (2.66)	-3.11 ± 1.04 (0.59)

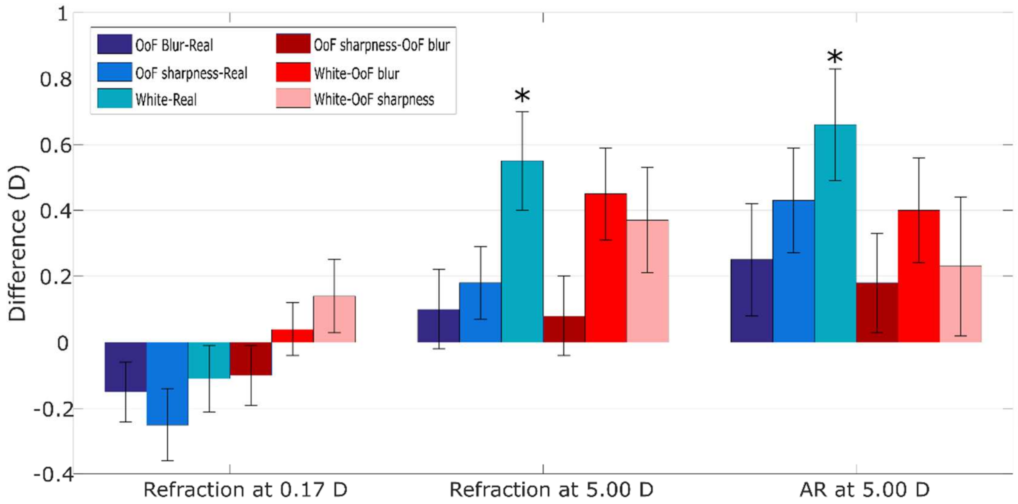

Figure 3. Differences between configurations for refraction (stimuli at 0.17 D and 5.00 D) and the accommodation response (AR) at 5 D. Error bars correspond to the standard error of the mean. *Statistically significant (Bonferroni post-hoc tests are applied only for refraction and AR at 5.00 D).

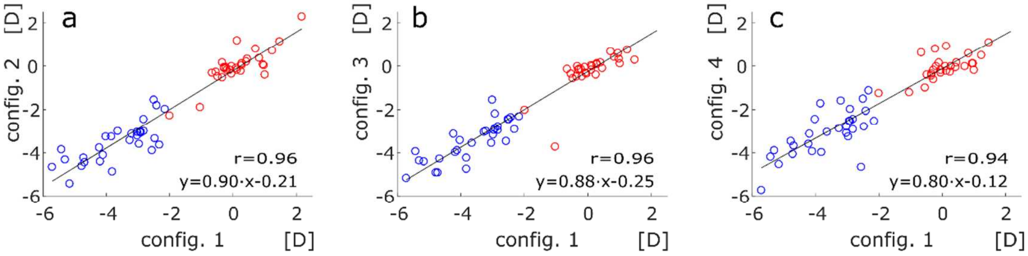

Figure 4. Correlation and regression coefficients for all configurations with respect the reference configuration 1 and for far and near refraction. Red dots refer to far distance refraction (0.17 D of AS) and blue dots to near distance refraction (5.00 of AS). All correlations are statistically significant (p<0.05).

DISCUSSION

The effect of apparent depth when stimulating accommodation by means of a Badal optometer was investigated. Two main variables were studied: the refraction and the accommodation response at 5.00 D, with the latter calculated as the near minus the far refraction.

In the case of refractions, a tendency toward higher lag and lead is observed at near and far distance targets, respectively, in Configurations 2, 3 and 4 than in natural viewing conditions (Config. 1). The highest lag is obtained when using the Badal target with no apparent depth cues (Config. 4). In this case, the mean difference with respect to the natural viewing configuration is -0.66 D (Figure 3), which agrees with the mean difference of -0.58 D obtained in a previous study under similar conditions but with a different autorefractometer.[1] This result~~s~~ showed that, ~~despite~~due to the real depth stimulus, the response may be ~~affected~~ influenced by the Mandelbaum effect~~s~~[23] (i.e., the out-of-focus information in the retinal periphery may behave as a conflicting stimulus and therefore bring the visual system towards its resting state of accommodation). However,~~,~~ when the central fixation target is appropriate to elicit accommodation (e.g., a Maltese cross) the peripheral depth cues (either real or apparent) contribute -on average- to more accurate AR responses.

Configuration 2 with apparent depth cues and simulated out-of-focus blur has the smallest mean AR difference (-0.25 D) with respect to the reference Configuration 1 at 5.00 D of AS. This mean difference is less than half the statistically significant difference obtained when comparing the white background configuration with the natural viewing condition (-0.66 D). Moreover, Configuration 2 has the best regression and correlation coefficients among all configurations compared with Configuration 1 (Figure 4a, 4b and 4c). These results suggest a significant improvement when stimulating accommodation in a Badal optometer using realistic stimulus with peripheral apparent depth cues.

Interestingly, this improvement seems to be affected by the consistency between the simulated depth and the real distance of the fixation target. The mean AR difference at 5 D of AS between the apparent depth cues condition with simulated out-of-focus sharpness (Config. 3) and the natural viewing condition is -0.43 D. In this case, the picture used at 5 D of AS in Configuration 3 was not consistent with the real scene since a depth cue was missing (the white cardboard in which the Maltese cross was printed). In consequence, the whole scene appeared sharp as if all the objects were at the same distance, which was unrealistic considering the size of both mannequins. Even if this consistency is not critical at far distances and in the periphery of the field of view since in these conditions the overall blur sensitivity decreases,[20,24] it contributes to a more inaccurate accommodation response according to our results. As shown in Figure 4a and 4b, the regression coefficients when comparing Config. 3 (OoF sharpness) with Config. 1 (natural viewing) are slightly worse than when comparing Config. 2 (OoF blur) with natural viewing.

We found a rather large inter-subject variability in all pairwise comparisons. Even though inter-subject variability is similar in magnitude to other accommodation studies that used the PowerRef,[25,26] it is important to disclose potentially important sources of variability when considering the results for individual subjects. Variability can be partially explained by fluctuations of accommodation (they can be of about 0.5 D for large AS[27]) and by the precision of the device.[16] These factors can be quantified by the within-subject standard deviation (Sw) shown in Table 2, which ranges from 0.31 to 0.59 D for the AR at 5 D. They represent, respectively, the 28% and 57% of the standard deviation of the differences found for the same variable.

Another factor that might have increased the variability found in all pairwise comparisons relates to peripheral refraction differences among subjects. All patients were corrected in fovea but not in the retinal periphery. It seems thus appropriate to infer that the peripheral refraction affected the amount of perceived out-of-focus blur and eventually the AR. Hartwig et al.[28] confirmed that the peripheral retina is sensitive to optical focus and found some evidence for less effective peripheral accommodation in myopes than emmetropes. In our study there were 19 myopes (spherical equivalent from -7.00 D to -0.50 D) and 11 emmetropes (spherical equivalent from 0.00 D to +0.75 D). To test the refractive error as a potential confounding factor, we calculated a mixed ANOVA considering the accommodation response as a dependent variable, the configuration type as a within-subject's factor (with 4 levels: Real, OoF blur, OoF sharpness and White) and the refractive error as a between-subject's factor (with 2 levels, Myopes or Emmetropes). We obtained only a significant effect for the configuration factor ($F_{3,\ 84}=4.67$, $p<0.01$). The refractive error ($F_{1,\ 28}=0.86$, $p=0.36$) and the interaction *Configuration*RefractiveError* were not statistically significant ($F_{3,\ 84}=0.35$, $p=0.79$). While it has been suggested that accommodation inaccuracies associated with myopia may be better analyzed in terms of age of onset (early-onset or late-onset) or progression (stable or progressing),[29,30] these results indicate that under the conditions of the study myopes accommodated similarly to emmetropes.[4,5,17]

Finally, pupil size differences and gaze position differences among configurations (Table 2) were not statistically significant in far and near distance. In consequence, refraction differences among configurations are unlikely to be explained by a change in depth of focus due to a change in pupil size and by instabilities of gaze.[31,32]

To summarize, for near targets seen through an optical system such as a Badal optometer, the accuracy of the accommodation response generally improves with a 2-dimensional stimulus with apparent depth cues and simulated out-of-focus blur in a relatively large field of view. Even though these conditions may not be adequate for all individuals, they can improve the overall visual comfort in those virtual reality systems that use a varifocal optical system to change the focal plane of a 2-dimensional surface.

DISCLOSURE OF FUNDING SOURCES

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DISCLOSURE OF POTENTIAL CONFLICT OF INTEREST

The authors have no proprietary or commercial interest in the materials presented.

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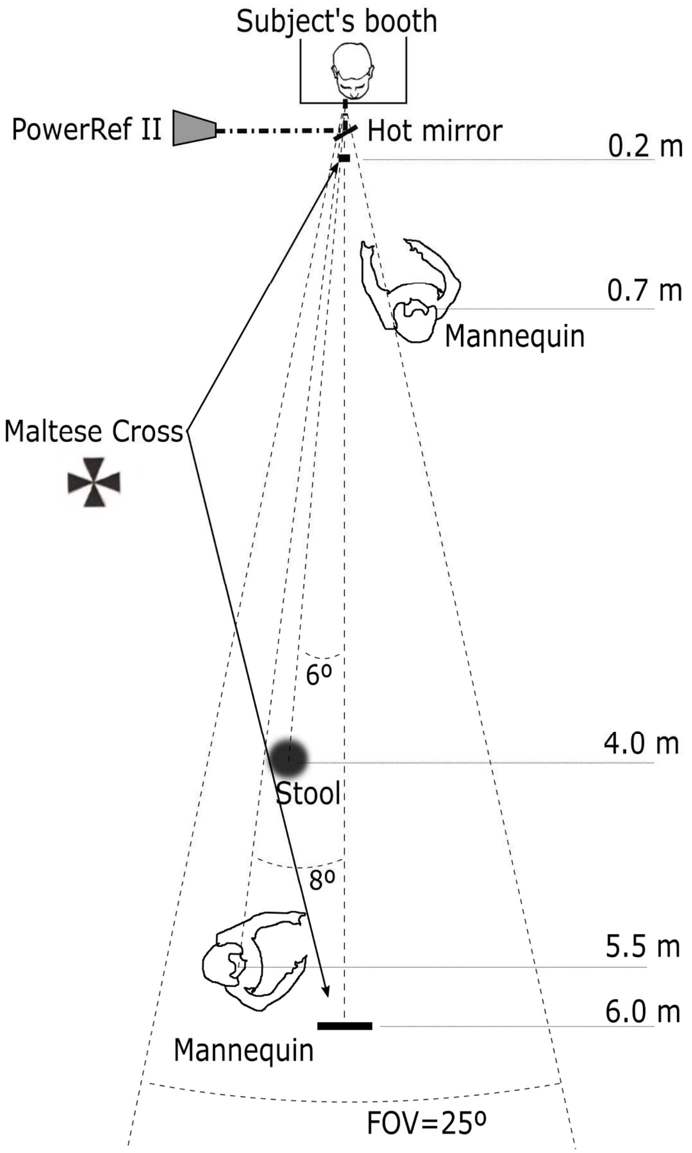

Figure 1. Top-view of the real 3-dimensional space setup (Configuration 1). Distances are shown in meters (m) in relation to the eye's pupil plane.
Figure 1

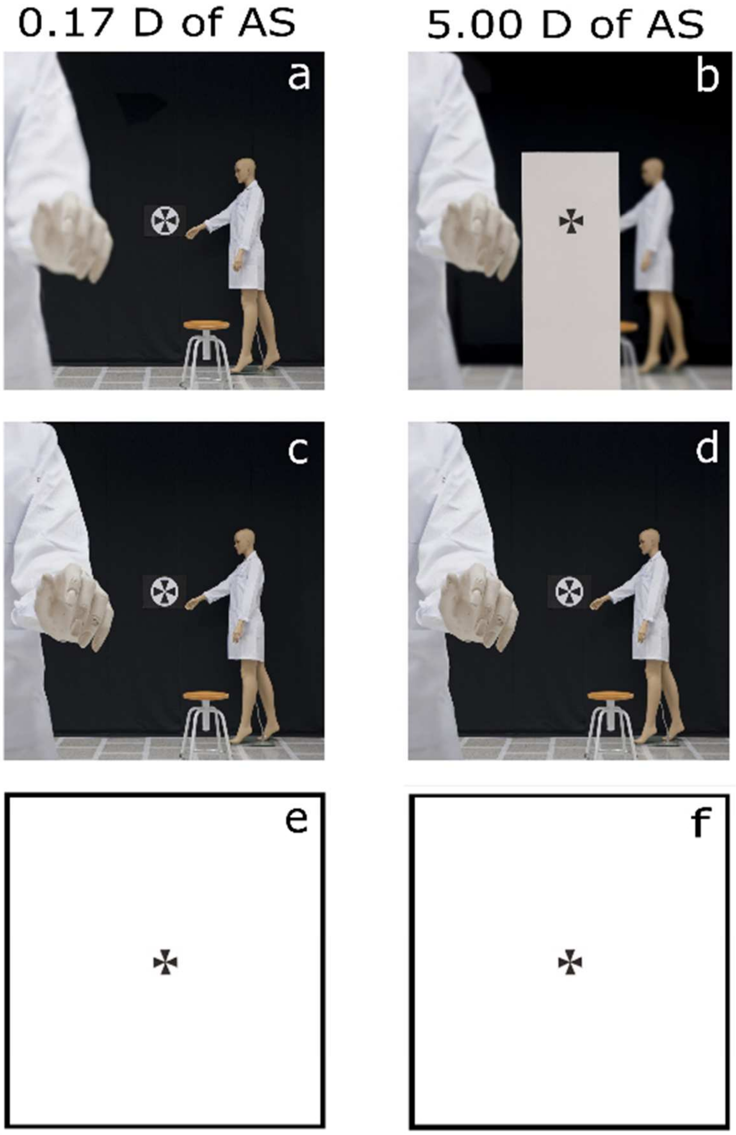

Figure 2. Accommodative stimulus used at 0.17 D (a, c, e) and 5.00 D (b, d, f) in the Badal optometer.
Configuration 2 (a, b), Configuration 3 (c, d) and Configuration 4 (e, f).
Figure 2
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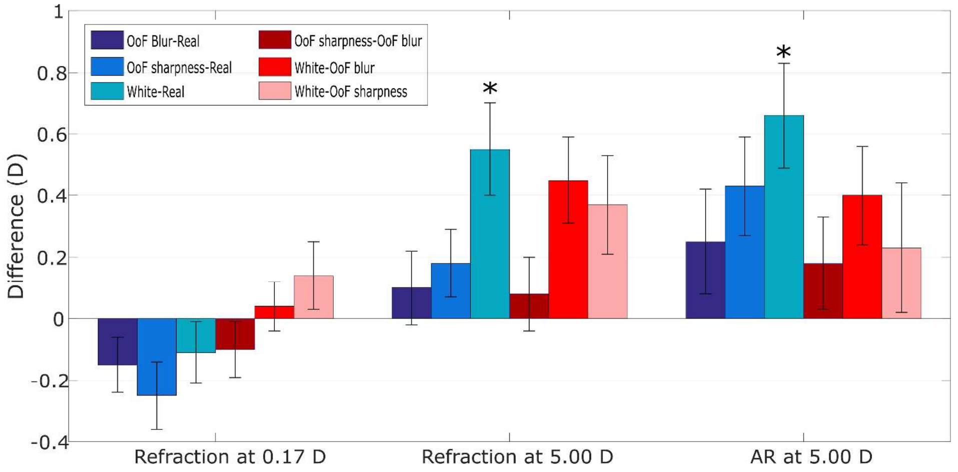

Figure 3. Differences between configurations for refraction (stimuli at 0.17 D and 5.00 D) and the accommodation response (AR) at 5 D. Error bars correspond to the standard error of the mean. *Statistically significant (Bonferroni post-hoc tests are applied only for refraction and AR at 5.00 D).
Figure 3

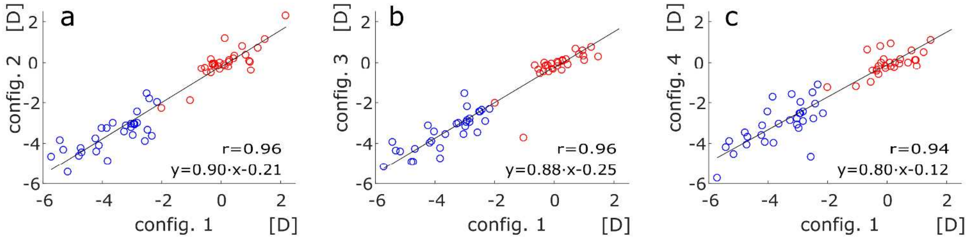

Figure 4. Correlation and regression coefficients for all configurations with respect the reference configuration 1 and for far and near refraction. Red dots refer to far distance refraction (0.17 D of AS) and blue dots to near distance refraction (5.00 of AS). All correlations are statistically significant ($p<0.05$).

Figure 4