EFFECT OF THE FIELD OF VIEW AND SEMANTIC CONTENT OF THE STIMULUS ON ACCOMMODATION STIMULATED WITH A VOLUMETRIC BADAL OPTOMETER

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Presented on date 19th July 2015

Registered at
Effect of the field of view and semantic content of the stimulus on accommodation stimulated with a volumetric Badal optometer

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Purpose: To investigate the effects of different field of view (FOV) and semantic content of the stimulus on accommodation stimulated with a volumetric Badal optometer and to compare these results with natural-viewing condition.

Methods: Accommodation was objectively measured with the PowerRef II at 0.17 and 5.00 D of accommodation stimulation (AS) on 17 young healthy patients. For both Badal targets and real free space targets (natural-viewing condition), at each AS, the FOV was discretely changed from 10º to 30º (10º-step). The volumetric system comprised the fixation stimulus and two fix planes at 0.17 D and 5.00D where besides the central stimulus, there are peripheral stimulus.

Results: The accommodative response obtained in a volumetric Badal system is more lead at far distance and more lagged at near distance than the natural-viewing condition. However, the repeated measures ANOVA did not show significant statistical differences among all the configurations at both far and near distance (p>0.05).

Conclusions: Accommodation stimulated in a volumetric Badal system is clinically comparable to accommodation stimulated using real targets in free space. Accommodation is not significantly affected by the semantic content of the scene nor the size of the field of view in a volumetric Badal system.

Keywords: Accommodation, Badal optometer, volumetric systems, field of view, stimulus.

1. Introduction
Accommodation is the capability of the eye to focus objects located either at far or near distances that are imaged behind the retina. In visual optics, accommodation can be stimulated using real targets in free space at different distances or by means of a Badal optometer. The Badal optometer is an optical system in which typically, the nodal point of the eye is placed at the anterior focal plane of the Badal system. With this configuration there are two important properties. On the one hand, the image vergence is proportional to the distance between the object and the front focal point of the system. On the
other hand, the angular size of the image is independent of object vergence. These optical properties can be seen with the Newton’s equation in air:

\[ X' = -xF^2 \]  \hspace{1cm} (1)

where \( F \) is the equivalent power (in diopters) of the Badal system, \( x \) is the object distance (in meters) to the object focal plane, and \( X' \) is the image vergence (in diopters) at the back focal point of the system, which also corresponds to the accommodation stimulation (AS) distance in diopters.

Notice that if the target is positioned at the posterior focal point of the Badal system, the resultant optical vergence at the eye is zero, i.e., the target is conjugate with the far point of an emmetrope. As the target is brought closer to the eye than the posterior focal point, optical convergence is increased and the target could be conjugate with the far point of a myope. Conversely, if the target is moved further from the eye and beyond the posterior focal point of the Badal system, optical divergence is created and the target could be conjugate with the far point of the hyperope.\(^2\) Thus, the Badal optometer is useful for ophthalmic instruments that aim to correct the spherical error and/or to stimulate accommodation.

Unfortunately, it is worth mentioning that the maximum negative image vergence is limited by the equivalent power of the Badal lens, i.e., if one considers a Badal optometer comprised by only one positive lens and neglects the lens thickness, then, the maximum negative image vergence occurs when the target is at the closest position with respect the Badal lens. In other words, \( x=f \) and \( X'_{max} = -F \). Despite there exists some optical solutions, this limitation needs to be considered in Badal systems with only one lens and specially in accommodation studies since the maximum accommodation stimulation is given by the focal length of the Badal lens. Interestingly, it has been shown that accommodation stimulated by means of a Badal optometer is not as in natural viewing conditions, i.e., using real targets in free space.\(^3\)\(^{-}5\)

It has been reported smaller accommodative responses when focusing Badal targets and it has been suggested that factors such as the field of view and depth cues are key aspects when stimulating accommodation. In these studies it is often used a small field of view (~5º) and simple stimulus such as a black Maltese cross on a white background, removing the presence of depth cues that could have helped the human eye to elicit a more accurate accommodative response.

Field of view is mainly limited by the optical design of the system and the requirements on display’s resolution. The lack of depth cues in a Badal optometer rely basically on the fact of displaying a 2-dimensional stimulus (i.e., a planar surface). In the last years, in order to deal with the lack of depth cues it has been proposed the concept of volumetric displays.\(^6\)\(^,\)\(^7\) It is a promising technology especially in the context of stereoscopic virtual reality systems that consists on superposing different focal planes. Therefore, a volumetric display allows -theoretically- a visual representation of an object in its three physical dimensions. The superposition of focal planes can be performed either by time\(^8\) or space multiplexing.\(^7\) In both cases, the number of focal planes and the separation between planes are limited by current technology.

To our knowledge, only one study investigate accommodation stimulated in a volumetric Badal system,\(^6\) however, it did not take into account important factors such as the field of view, greater accommodative stimulus such as 5 D or the type of stimulus displayed. Considering all these, the purpose of this study was, firstly, to investigate the effects of different FOV on accommodation stimulated with a volumetric Badal optometer; secondly, to compare these
results with the natural viewing condition; and finally, to compare the already used target with stimulus semantic content with the same target but without this semantic content.

2. Methods
The study followed the tenets of the Declaration of Helsinki, and all subjects gave informed written consent. Subjects were recruited from staff and students of the Faculty of Optics and Optometry at the Technical University of Catalonia (UPC, Terrassa, Spain). Criteria for inclusion were best spectacle-corrected visual acuity of 0.10 logMAR or better and no history of any ocular condition, surgery and/or pharmacological treatment. Patients wearing spectacles were excluded to avoid measurement artefacts caused by reflections from lens surfaces. Consequently, only emmetropes and contact lens wearers were included, with spherical and cylindrical components of over-refractions within ±0.50 D. The upper age limit was set at 30 years old to help ensure good amplitude of accommodation. Mean age ± standard deviation (SD) of 17 subjects were 25 ± 3 years (22 to 30 years).

2.1. 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 at a sampling frequency of 25 Hz.\textsuperscript{9,10} Alignment between the PowerRef II and the patient eye was through a 50-mm squared Hot Mirror (i.e., reflects IR, transmits visible) placed 2.50 cm from patient’s pupil plane (figure 1).

![Figure 1](image)

Figure 1. Top-view of the real 2-dimensional space setup (configuration 1).

The setup consisted on the PowerRef II autorefractometer and different configurations to stimulate accommodation. Autorefractometer measurements were taken at target distances, or
equivalent positions in a Badal system, of 6 m and 20 cm, corresponding to accommodation stimuli of 0.17 D and 5.0 D, respectively. In all cases, luminance of the stimulus was constant at 500lux and the fixation target was a Maltese cross subginting 2.5°. Peripheral stimulus subtended 13° at 30° of FOV, the rest 3° were obtained from the 1.5° of separation between the central stimulus and the peripheral one.

The first configuration consisted on natural viewing conditions, i.e., stimulating accommodation with 3-dimensional targets in free space. The overall stimulus consisted on two peripheral stimuli at fix distances of 0.20 m for the left side stimulus and 6.0 m for the right side stimulus; and a fixation target that was places either at 0.20 m or 6.0 m depending on whether accommodation was stimulated at 5.00 D or 0.17 D, respectively. The peripheral stimuli were two planar images designed to provide some peripheral depth cues at different focal planes. These images aimed to represent two semantic well-known entities: an adult and a child at a distance of 6 meter (right side stimulus), and a hand holding a mug at 0.2 meter distance (left side stimulus). In this configuration the FOV was 30°.

The second configuration comprised a Badal optometer (Badal lens f=100 mm, diameter=49 mm). The stimulus was the same used in the previous configuration (real scene) but scaled to be seen through the Badal lens (figure 2a and 2b). Only in this configuration, refraction were measured using 3 different diaphragms that limit the size of the FOV to 30°, 20° and 10°.

The third configuration consisted on the same previous Badal optometer but the images used as peripheral stimuli were processed in order to remove the semantic content of the scene but preserving the same spatial frequency content. To do that, the phase of the Fourier spectra of the images was randomized. The FOV used for this configuration was 30°. As it can be seen in figure 2, for each configuration there is always one peripheral stimulus defocused relatively to the Maltese cross plane. A summary of each configuration can be found in table 1.

<table>
<thead>
<tr>
<th>Config.</th>
<th>SM</th>
<th>FOV [°]</th>
<th>Scene (label)</th>
<th>AS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Real target</td>
<td>30</td>
<td>Stimulus with semantic content (R_Sem30)</td>
<td>0.17 &amp; 5.00 D</td>
</tr>
<tr>
<td>2</td>
<td>Badal target</td>
<td>30, 20, 10</td>
<td>Stimulus with semantic content (B_Sem30, B_Sem20, B_Sem10)</td>
<td>0.17 &amp; 5.00 D</td>
</tr>
<tr>
<td>3</td>
<td>Badal target</td>
<td>30</td>
<td>Stimulus without semantic content (B_Rnd30)</td>
<td>0.17 &amp; 5.00 D</td>
</tr>
</tbody>
</table>
2.2. Examination Protocol
Firstly, an optometric examination was performed. The refractive state was obtained with a subjective refraction procedure, with the endpoint criteria of maximum plus power consistent with best vision. The eye with best visual acuity was chosen for the measurements. Monocular amplitude of accommodation was measured by means of push-up method. After the optometric examination, the patient was blindfolded and moved to the measurement room. Thanks to the patient blindfolding and the sheetrock surrounding the chin rest, the patient was not aware of the real dimensions of the setup nor the room, which could have biased the accommodative
response.\textsuperscript{12,13} Once the participant was sit in front of the chin rest, the patients were left 5 minutes blindfolded to ensure that all of them started from the same baseline accommodative level (i.e., a wash-up accommodation procedure).\textsuperscript{12} Thereafter, the accommodative response was measured for the previously described configurations. The non-tested eye was occluded with an eye-patch. The spherical equivalent of the eye was recorded over a period of 10 seconds in each case. The accommodation responses (AR) for 5.0 D stimuli were determined by subtracting the refractions for the 0.17 D stimulus from the refractions for these stimuli. The accommodation responses were thus negative, in order to be consistent with refractions. The measurement order of each configuration was randomly selected.

2.3. Statistical analysis
The significance was set at 0.05 and the statistical analysis was performed using commercial SPSS v22 (IBM Corp., USA). Normality of each variable was checked by applying the Shapiro-Wilk test and comparing the skewness and kurtosis statistics to the standard error. The repeated measures ANOVA was used to test the within-participant effects (i.e., the overall significant difference between each configuration). Where the assumption of sphericity was violated, the Greenhouse-Geisser correction was used. When significance was obtained, pairwise comparisons were examined by t-tests with Bonferroni correction.

3. Results
17 eyes of 17 people (age range 22 to 30 years) participated in the study. One eye of each subject was included, with mean corrected logMAR visual acuity ± SD of –0.16 ± 0.07 (−0.30 to −0.06) and mean subjective amplitude of accommodation ± SD of 6.79 ± 1.76 D (range 3.50 to 10.00 D).

All eyes had a best spectacle-corrected visual acuity of at least 0.0 (logMar notation) or higher. The post hoc power analysis carried out through the open source GPower\textsuperscript{14} showed a mean power effect of 0.99 for a sample size of 17 subjects and 5 repetitions (i.e., configurations) for each variable studied.

Table 2 presents the mean ± standard deviation for each configuration and for the three variables studied: spherical equivalent (SE) at 0.17 D, SE at 5.00 D and AR at 5.00 D. The statistical significance (p-value) obtained from the Shapiro-Wilk test are also shown in this table.

<table>
<thead>
<tr>
<th>Config.</th>
<th>SE at 0.17 D of AS</th>
<th>SE at 5.00 D of AS</th>
<th>AR at 5.00 D of AS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Sig.\textsubscript{SW}</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>R_Sem30</td>
<td>0.21 ± 0.64</td>
<td>0.56</td>
<td>-3.65 ± 1.27</td>
</tr>
<tr>
<td>B_Rnd30</td>
<td>-0.16 ± 1.11</td>
<td>0.05</td>
<td>-3.43 ± 0.75</td>
</tr>
<tr>
<td>B_Sem30</td>
<td>0.13 ± 0.49</td>
<td>0.86</td>
<td>-3.07 ± 0.85</td>
</tr>
<tr>
<td>B_Sem20</td>
<td>0.14 ± 0.44</td>
<td>0.85</td>
<td>-3.20 ± 1.01</td>
</tr>
<tr>
<td>B_Sem10</td>
<td>0.06 ± 0.53</td>
<td>0.59</td>
<td>-3.07 ± 0.87</td>
</tr>
</tbody>
</table>

Table 3 shows the results of the three repeated measures analysis of variance (ANOVA) performed for each variable studied. Both the SE at 0.17 D of AS and the AR at 5.00 D of AS are not statistically different among configurations. However, there is statistical significance for the Spherical Equivalent at 5.00 D of AS. Note that for simplicity the post-hoc Bonferroni test is not shown since no pairwise comparisons turned out to be statistically significant.
Table 3. One-way repeated measures ANOVA for each data group. SE: Spherical Equivalent. AS: Accommodation Stimulation. Sig.: statistical Significance (p-value). DF: Degrees of freedom.

<table>
<thead>
<tr>
<th>SE at 0.17 D of AS</th>
<th>SE at 5.00 D of AS</th>
<th>AR at 5.00 D of AS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sig.</td>
<td>0.36</td>
<td>0.03</td>
</tr>
<tr>
<td>F statistic</td>
<td>1.01</td>
<td>3.51</td>
</tr>
<tr>
<td>DF</td>
<td>1.55</td>
<td>2.59</td>
</tr>
<tr>
<td>Error</td>
<td>21.69</td>
<td>38.92</td>
</tr>
</tbody>
</table>

4. Discussion

It was investigated the effects of the field of view and semantic content of the stimulus on accommodation stimulated with a volumetric Badal optometer. Three main variables were studied: the refraction at 0.17 D of AS, the refraction at 5.00 D of AS and the accommodative response at 5.00 D of AS, with the latter calculated as the near refraction minus the far refraction.

Firstly, it can be seen a tendency for more lagged refractions at near and more lead refractions at far distance targets in Badal-like configurations than in natural viewing conditions (config. 1), which is in agreement with the resting state of accommodation hypothesis. The resting state of accommodation does not correspond to a viewing distance of optical infinity for the emmetropic eye as it is said in early assumptions. The resting state represents a balance between the near and far point and often an estimate of this neutral point is made by assessing accommodation in complete darkness.  

Surprisingly, there aren’t any significant statistical differences among configurations in any of the three variables, thus stimulating accommodation with a volumetric Badal System is statistically equivalent than the natural viewing conditions. However, these differences are clinically significant, e.g., in one of the best cases the accommodative response for B_Sem20 is -3.34 D and for R_Sem30 is -3.86 D. Hence, among these two values exists a mean difference of 0.52 D, higher than the 0.25 D clinical threshold. Moreover, it is worth mentioning the large dispersion present in all data sets, especially in the accommodative response at 5 D of AS. The standard deviation is ±1.27 D for R_Sem30 and ±0.89 D for B_Sem10. This dispersion may mask a significant statistical effect if the sample is small. However, in this study the statistical power found in a post-hoc power analysis turns out to be good, suggesting that a sample of 17 people is enough for a repeated measures ANOVA with 5 groups. Therefore, the spread of data may result because of the instrument repeatability, the accommodative fluctuations (which can achieve values of 0.50 D in amplitude for high accommodative stimulus), or even depth of focus changes due to changes in pupil diameter among configurations.

Regardless statistical significance and data variability, one of the main objectives of this study was to observe the effect of FOV size in the accommodative stimulation. It was not found a clear effect of FOV in AS at 5.00 D. This could be explained because between 10º and 30º FOV the accommodative stimulations only affects on the peripheral retina without causing any effect on the macula. It is well-known that blur sensitivity decreases with the stimulus eccentricity while the depth of focus increases. Accordingly, it was expected not huge differences between 10º and 30º. Hence, the results suggest that in order to stimulate the accommodation in a volumetric virtual reality system, a FOV of 10º is enough, this finding might be useful for
optical designers of virtual reality systems that seek high resolution systems capable of stimulating accommodation properly.

Finally, the other principal objective of this study was to observe whether the semantic content of a scene induces significative changes. The differences are not statistically nor clinically significant (B_Sem30 is -3.22 D and B_Rnd30 is -3.28 D). This partially agrees with the study of Busby et al.\(^{19}\) that concludes that apparent depth cues do not significantly affect the accommodative response, although, it is important to highlight that they did not use any volumetric Badal system and they found larger differences than the ones found in this study. Moreover, in this study depth cues were separated between abstract-to-discern and well-known apparent depth cues. To obtain this differentiation the spatial frequency spectrum was kept constant (note that the frequency spectrum is a key aspect for proper stimulation of accommodation).\(^{20}\) In this case, it was demonstrated that the accommodative response is driven principally by blur (which is tightly dependant on the accommodative stimulation distance and the frequency spectrum of the stimulus) and not significantly because of the semantic content of the scene. Thus, neglecting the semantic content of an accommodative stimulus is not as important as it is to keep a wide frequency spectrum of the stimulus.

5. Conclusions
It has been demonstrated that the accommodative response stimulated by means of a Badal optometer is not as accurate as in natural viewing conditions and further studies might consider more focal planes in order to introduce more depth cues and reduce these mean differences up to clinical acceptable values (<0.25 D).

As well, based on our results, the accommodative response does not seem to be affected by different field of views from 10° to 30° which is likely due to the fact that accommodation is mainly driven in the near periphery (<10°). Further studies might include also smaller FOV’s.

Finally, taking into account the semantic content of the peripheral stimulus, our results suggested that the accommodative response is not significantly influenced by the semantic information of the stimulus, it is mainly driven by the blur content, which is directly related with the frequency spectrum and the accommodative stimulation distance.

Acknowledgments
I would like to thank my supervisor, Prof. Jaume Pujol and Dr. Carles Otero for their help and advices throughout the course of this work.

References