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Assessing the accommodation response after near visual tasks using different handheld electronic devices

Avaliação da resposta de acomodação após tarefas visuais próximas usando diferentes dispositivos eletrônicos portáteis

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ABSTRACT

Purpose: To assess the accommodation response after short reading periods using a tablet and a smartphone as well as determine potential differences in the accommodation response at various stimulus vergences using a Hartmann-Shack aberrometer.

Methods: Eighteen healthy subjects with astigmatism of less than 1 D, corrected visual acuity of 20/20 or better, and normal findings in an ophthalmic examination were enrolled. Accommodation responses were obtained under three different conditions: accommodation system of the eye relaxed and visually stressed with a tablet and an smartphone for 10 min, at a distance of 0.25 m from the subject's eyes. Three measurements of accommodation response were monocularly acquired at stimulus vergences ranging from 0 to 4 D (1-D step).

Results: No statistically significant differences were found in the accommodation responses among the conditions. A moderate but gradually increasing root mean square, coma-like aberration was found for every condition. Conversely, the spherical aberration decreased as stimulus vergences increased. These outcomes were identified in comparison to the one-to-one ideal accommodation response, implying that a certain lag value was present in all stimulus vergences different from 0 D.

Conclusions: The results support the hypothesis that the difference between the ideal and real accommodation responses is mainly attributed to parameters associated with the accommodation process, such as the near visual acuity, depth of focus, pupil diameter, and wavefront aberrations. The wavefront aberrations were dependent on the 3-mm pupil size selected in this study. The accommodation response was not dependent on the electronic device employed in each condition, and it was mainly associated with young age and level of amplitude of accommodation of the subjects.

Keywords: Accommodation, ocular; Computers, handheld; Smartphone

RESUMO

Objetivo: *Avaliar a resposta de acomodação após períodos de leitura curtos usando um* tablet *e um* smartphone*, bem como para determinar potenciais diferenças na resposta de acomodação em estímulos de várias vergências com uma aberrômetro Hartmann-Shack.*

Método: *Dezoito indivíduos saudáveis com astigmatismo inferior a 1 D, apresentando acuidade visual corrigida de 20/20 ou melhor com exame oftalmológico normal foram avaliados. As respostas acomodativas foram obtidas em três condições diferentes: sistema de acomodação com o olho relaxado, e visualmente estressado com um* tablet *e um* smartphone *por 10 min, a uma distância de 0,25 m dos olhos dos sujeitos. Três medidas de resposta acomodativa foram obtidas monocularmente com estímulos cujas vergências variaram de 0 a 4 D (intervalos de 1 D).*

Resultados: *Não houve diferença estatisticamente significativa entre as respostas acomodativas em todas as condições. Foi observada moderada aberração do tipo coma com aumento progressivo para cada condição, enquanto houve diminuição da aberração esférica com o aumento das vergências do estímulo. Estes resultados foram identificados em comparação com a resposta acomodativa de um-para-um ideal, o que implica que um certo valor de desfasagem estava presente em todos os estímulos com vergências diferentes de 0 D.*

Conclusões: *Os resultados apoiam a hipótese de que a diferença entre as respostas acomodativas ideal e real é atribuída principalmente a parâmetros tais como a acuidade visual para perto, profundidade de foco, diâmetro pupilar e aberrações de frente de onda, associados ao processo acomodativo. As aberrações de frente de onda foram dependentes do tamanho da pupila de 3 mm, selecionado neste estudo. A resposta acomodativa não foi dependente do dispositivo eletrônico empregue em cada condição e foi associada principalmente à idade jovem e ao nível da amplitude de acomodação dos sujeitos avaliados.*

Descritores: *Acomodação ocular; Computadores de mão/utilização; Computadores/utilização; Smartphone/utilização*

INTRODUCTION

The use of computers and digital electronic devices for both professional and non-professional activities has become more prevalent in modern society globally[(1)]. It has been proven that approximately 75% of companies have incorporated desktop computers into the workplace[(2)]. Meanwhile, reading from digital electronic screens is no longer exclusively restricted to desktop computers located in the workplace. The use of laptops, tablets, electronic book readers, smartphones, and other electronic devices has been expanded outside the workplace to the home or other locations[(1)].

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Individuals of all ages display preferences for handheld electronic devices (e.g., smartphones and tablets) for written communication (e.g., text messaging, e-mail, and internet access). This is resulting in the replacement of hardcopy printed materials as electronic devices have become an integral part of individuals' daily lives[(3)].

However, the relatively small screen and text size of such devices require close working distances, affecting the accommodation needed from the crystalline lens[(4)], which is required for having clear and sharp vision at such distances[(5)]. Therefore, continuous contraction of the extraocular and ciliary muscles of the eye is needed. Thus, the prolonged use of such devices in close working distances may result in the development of symptoms, such as eyestrain, ocular discomfort, dry eye, diplopia, and blurry vision[(6)].

Nonetheless, accommodation is one of the most important visual processes of the human eye, and thus, several new optical instruments have been designed to appraise the accommodation process (e.g., biometric and optical methods) in recent years[(7)]. One of the most widely accepted and powerful instruments for evaluating the dynamic components of accommodation is the wavefront aberrometer[(8)]. It is well known that the accommodation process has a direct effect on the wavefront of the human eye. Using a wavefront aberrometer, which describes the wavefront at every point of the eye's pupil diameter, changes in the wavefront can be easily assessed[(9,10)].

Because of the proliferation of electronic devices in the last decade, studies have been conducted[(11)] to determine whether reading on electronic screens influences the optical quality of the human eye. At present, a definitive conclusion has not been established. Additionally, to assess the accommodation process of the human eye, it is preferable to use a non-invasive modality (i.e., wavefront sensing aberrometry).

Therefore, the aim of this study was to assess the accommodation response after short reading periods using a tablet and a smartphone as well as to determine potential differences in the accommodation response at various stimulus vergences using a Hartmann-Shack aberrometer.

METHODS

Subjects

Eighteen young adult subjects (mean age: 28 ± 1.9 years, range: 25-30 years) participated in the study. Astigmatism was limited to ≤1.00 D, and anisometropia was limited to <2.00 D. All subjects had normal corrected visual acuity (20/20 or better), no ocular pathology, no binocular vision anomalies, no previous conducted ocular surgery, and normal clinical amplitudes of accommodation for their ages. This clinical study was approved by the Review Board of the University of Valencia-Optometry Research Group, and it was conducted according to the tenets of the Declaration of Helsinki. Informed consent was obtained from each subject after providing a verbal explanation of the nature and possible consequences of the study.

Equipment

The crx1 instrument (Imagine Eyes, Orsay, France) was used to measure the wavefront aberrations of one eye in each subject (Figure 1). It employs a square array of 1024 microlenses and a near-infrared light source with a wavelength of 850 nm. An internal microdisplay is used to project the target, and the Badal system is employed to change its vergence. To control the accommodation process, a Maltese cross is used as the target. A precise alignment of the subject's pupils is required, and these parameters are controlled with an additional charge coupled device camera. Head movements were reduced by employing a chin and forehead rest.

Prior to data collection, commercially available software, namely HASO-CSO (Imagine Eyes), was used to correct the internal aberrations. Hence, during the wavefront measurement, an aberration-free optical system was maintained. Consequently, the wavefront aberrometer is capable of obtaining the ocular aberrations as Zernike coefficients up to the eighth order. Despite this, Zernike coefficients up to the sixth order were considered in the present study. Likewise, the wavefront data might be used to calculate the wavefront refraction based on the least square fit of a spherical-cylindrical surface[(12)].

An iPad mini and an iPhone 4S (Apple Inc., California, USA) were employed to perform the visual tasks. The iPad mini and iPhone 4S are characterized by screen sizes of 7.9 and 4.5 in, respectively. The relative small screen and text size of such handheld electronic devices were suitable for visually stressing the accommodation state of the eye.

Reading task

The reading material consisted of text with black letters displayed on a white background. The text was displayed on the iPad mini and iPhone 4S screens with a font size corresponding to 20/20 visual acuity. To calculate the correspondence of the text displayed on both the iPad and iPhone 4S screens, the minimum separation between two lines that a subject with visual acuity equal to 1.0 could identify was estimated. This value was expressed as an angle of 1 minute of arc (1/60 of a degree). Prior to that, the height of a letter (e.g., capital X) was measured for both electronic devices by employing an electronic digital caliper. Then, the height correspondence (in mm) was estimated, resulting in font sizes of 5 and 3 (in Times New Roman) for the iPad and iPhone 4S, respectively.

Both devices were placed at a distance of 0.25 m from the subject's eyes. On average, the luminance of the screen of both devices was adjusted to be constant and equal to 200 cd/m^2. Subjects were instructed to read the text silently for 10 min.

Experimental procedure

The experiment was divided into three conditions, each followed by a different accommodation state. In the first condition, the accommodation state of the eye was relaxed, whereas it was visually stressed in the two other conditions. In this aim, reading tasks were performed using the two previously described electronic devices. More specifically, text for reading was displayed on both the iPad mini and iPhone 4S. In all conditions, the tasks were performed monocularly to solely assess accommodation and not convergence.

The accommodation responses were measured under three different conditions: (i) relaxed, (ii) after reading 10 min on an iPad mini, and (iii) after reading 10 min on an iPhone 4S. After completing

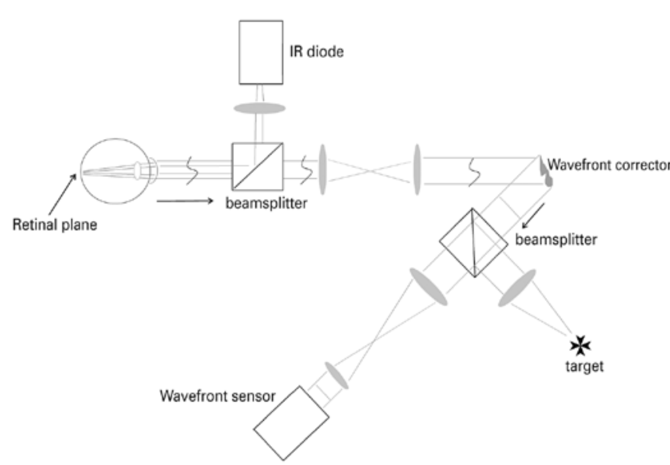

Figure 1. Schematic layout of the instrument used as a wavefront aberrometer.

each condition, three measurements of accommodation response were monocularly acquired at stimulus vergences of 0, 1, 2, 3, and 4 D, employing the irx3 Hartmann-Shack aberrometer. Thus, 15 wavefront measurements were recorded per accommodation state, giving a total of 45 measurements for each eye. The subject was allowed to blink prior recording a measurement to avoid increased tear film aberration that might otherwise have occurred during an extended inter-blink interval[13]. In each of the aforementioned conditions, the measurements were collected on different days by randomly providing the devices to the subjects.

Data analysis

The wavefront data were exported as Zernike coefficients up to the sixth order rescaled to a 3-mm pupil size using the method described by Schwiegerling[14]. The Zernike polynomials are orthogonal, and thus, the Zernike defocus is independent of the higher order aberrations and their certain interaction, which mainly influences the retinal image quality. Therefore, to solely identify the response of the eyes to the accommodation stimuli, the Zernike defocus is commonly used[12,15]. In the present study, the accommodation response was determined from the measured wavefront using the least squares fitting procedure provided by the Zernike defocus, which is known as a surface fitting procedure. The accommodation response was estimated in diopters employing the following equation:

$$M = \frac{C_2^0 4\sqrt{3}}{r^2}, \quad (1)$$

where C_2^0 is the second-order Zernike coefficient for defocus in µm and r is the pupil radius in mm[16].

To identify the image quality changes during accommodation, the spherical aberration was analyzed for all conditions because it has been confirmed to be the main higher-order aberration that contributes to these changes[12]. The same applies for coma, which is subjected to various changes during accommodation[15]. Hence, the sum of the third and fifth order Zernike coefficients and the fourth order Zernike coefficient were utilized to calculate the root mean square (RMS) of coma-like and spherical aberrations, respectively.

Using IBM SPSS Statistics software v22.0 (Armonk, NY, USA), one-way ANOVA was performed to identify the influence of each device on the accommodation response. Then, a post-hoc analysis (Tukey's honest significant difference test) was conducted to determine the significantly different mean values for each condition. A p-value of less than 0.05 was considered statistically significant.

RESULTS

To obtain the values of the accommodation response, the second-order Zernike coefficient (defocus) was converted into diopters using the previously described formula (Equation 1). Figure 2 presents the average of three consecutive measurements for each condition and stimulus vergence considered in this study.

It was anticipated that the accommodation response would be described as the inverse of a fixed distance by the formula $A = \frac{1}{d}$, in which A refers to accommodation (in diopters) at a certain distance d (in meters). All of the obtained accommodation responses had a shift with respect to the theoretical line, demonstrating that a certain value of lag was present for all stimulus vergences. This was also evident in the data collected by Ciuffreda et al.[17], although a greater lag of accommodation was found in the present study (Figure 3).

When analyzing the higher-order aberrations, a moderate but gradually increasing RMS of coma-like aberrations with accommodation at each stimulus vergence was obtained for all subjects, as illustrated in figure 4.

Additionally, it was verified that as the accommodation demand increased (i.e., with the stimulus vergences), the spherical aberration decreased (i.e., reducing its positive value), as shown in figure 5.

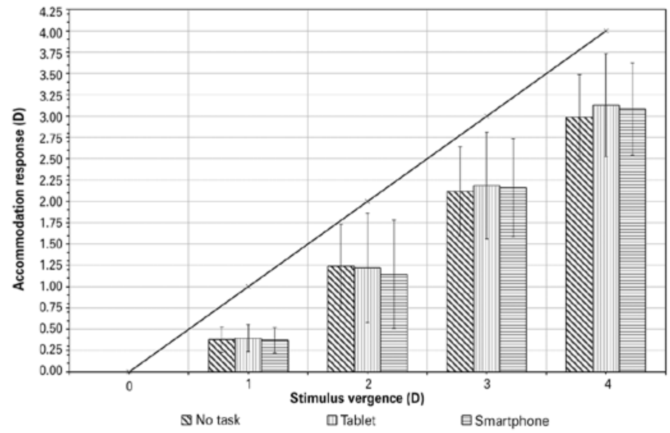

Figure 2. Comparison between the different accommodation states (± standard deviation) for each condition and stimulus vergence (D). The dashed line shows the theoretical response of the accommodation process (equal accommodation response for each stimulus vergence).

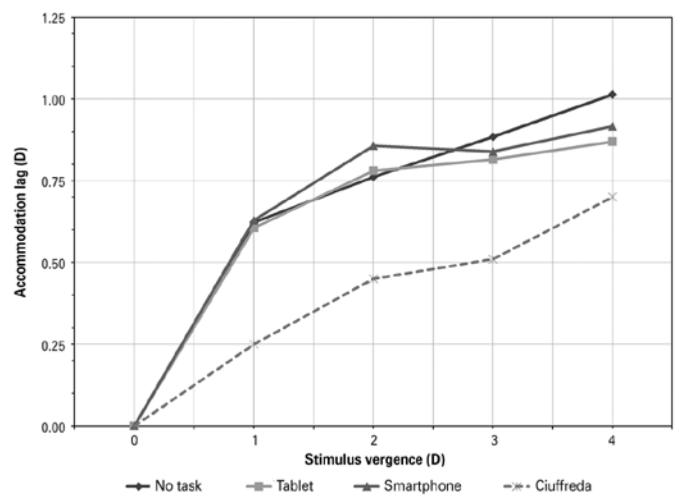

Figure 3. Lag of accommodation obtained for all conditions compared with the replotted data of Ciuffreda et al[17].

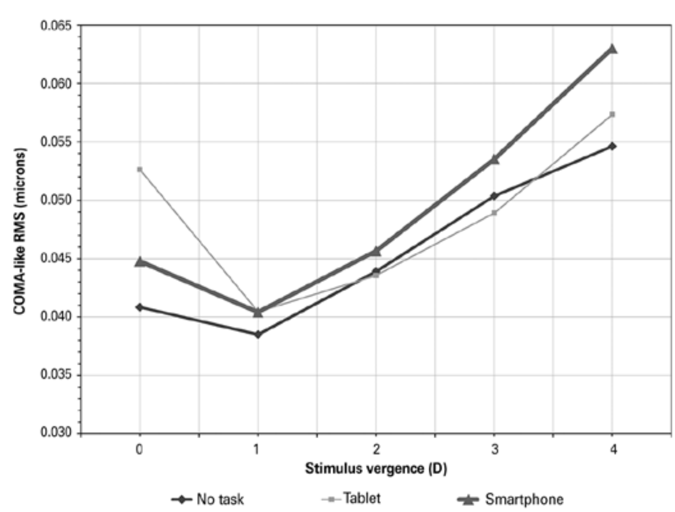

Figure 4. The root mean square derived from the third- and fifth-order coma aberrations.

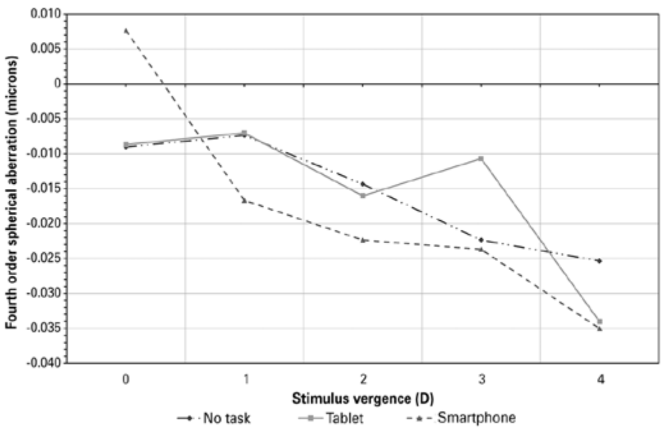

Figure 5. The spherical aberration pattern in relation to the different stimulus vergences and conditions for a single subject.

As previously mentioned, a statistical analysis was conducted to estimate the variance over the different stimulus vergences for the three accommodation conditions. In conclusion, no statistical difference ($p>0.05$) was found among the different conditions.

DISCUSSION

In the present study, the accommodation response was assessed after short reading periods using a tablet and a smartphone. The assessment was performed using a Hartmann-Shack aberrometer and different stimulus vergences.

In recent years, a large amount of handheld electronic devices have reached the market, with tablets and smartphones being the most adopted electronic devices in modern society along with personal computers. Several studies demonstrated the massive increase in the use of such electronic devices in individuals' daily lives. For example, a study conducted by Takeda et al.[18] revealed that in the US, the percentage of visual display terminal operators (VDTOs) jumped from 30 to 60% over a 5-year period. However, VDTOs experience a high degree of visual strain, as proved by the same study. In particular, the degradation of accommodation reported after sustained work by VDTOs exhibited a strong correlation with visually demanding tasks, depletion of accommodation, and visual fatigue. Therefore, to employ such technology for reading tasks, an excellent near visual acuity is required because it is strongly associated with the accommodation process.

Moreover, Sheedy and Shaw McMinn suggested that a subject should have a near visual acuity approximately three times higher than normal to easily read text on an electronic display[19]. Nonetheless, Bababekova et al. stated that the previously described rule does not coincide with any objective evidence[1]. Thus, the authors recommended a clear association between the pixel density of a certain electronic device (e.g., pixel/mm) and the number of pixels per letter height, a parameter considered in this study.

Despite the near visual acuity, additional parameters, such as depth of focus (DoF), pupil diameter, and wavefront aberrations, are associated with the accommodation process. In particular, Tucker et al. proved that the pupil diameter is inversely correlated with the DoF and directly correlated with the wavefront aberrations of the eye[20]. Hence, for the experimental procedure of this study, a pupil diameter of 3 mm was selected.

It is well established that the eye wavefront is essentially formed by the wavefront of both the cornea and crystalline lens[21,22], and thus, it is affected by the accommodation process. For this reason, in the current study, a wavefront aberrometer was employed to calculate the total eye wavefront. Another factor that led to the use of this instrument is that it objectively evaluates the accommodation process[10], bypassing the limitations associated with the subjective evaluation of the accommodation process (e.g., non-differentiation of a passive DoF, changes in ocular aberrations or accommodation power).

To estimate the accommodation response at different stimulus vergences for all conditions, the defocus aberration was employed. The findings for each condition were only compared among subjects in the same group. The obtained accommodation responses demonstrated a lag of accommodation for all stimulus vergences and conditions. These results are in agreement with those obtained by Ciuffreda et al.[17], although a greater lag of accommodation was evident in the current study.

Additionally, several parameters were considered to maintain good visual performance. Particularly, the ambient illumination affects the visual performance and causes visual fatigue[23]. Hence, ambient illumination was fixed at 300 lux during the experiments to prevent any reduction of the contrast of the displays employed and interference of glare with the near visual tasks. Furthermore, the screen reflectivity influences the image quality, meaning higher visual performance was recorded with a lower screen reflectance coefficient[24]. Consequently, two electronic devices produced by the same company were employed to reduce any potential differences in terms of data and screen technology or reflectivity.

Both visual tasks were performed at a distance of 0.25 m, which is the common reading distance for the subjects' ages[25]. A shorter distance could further alter the accommodation response. For this reason, the selection of a visual task (e.g., watching a video, playing a game) over a range of various distances could be an interesting subject for evaluation in the future.

The current study did not aim to correlate the accommodation response after reading text on a hardcopy printed material with that using an electronic device. Meanwhile, a study conducted by Hue et al. compared the performance of subjects when reading using printed material and two types of handheld electronic devices (i.e., Amazon Kindle e-reader, Apple iPod)[3]. In particular, the authors found that the reading speed was significantly lower when reading from the iPod in comparison to that when reading printed material. This was attributed to the relatively small screen of the electronic device. Additionally, no differences in reading speed were found when reading on the Kindle and reading printed material.

Another finding of this study was a moderate but gradually increasing RMS of coma-like aberration with the accommodation state, as previously described by Cheng et al.[26]. The authors reported a relative influence on the RMS of coma-like aberration due to the vertical shift of the lens throughout the accommodation process. López-Gil et al. found that the increase of the third-order aberration was dependent on the subjects' variability[27]. Nevertheless, the findings of additional studies did not indicate that the presence of third-order aberrations play a crucial role in the accommodation response[28].

Additionally, it is widely established that spherical aberration is most strongly linked to accommodation[9,12,29]. Mostly, it has been identified that an increase in accommodation demand causes a decrease in spherical aberration. This is due to the conicity of the lens, which may also originate from the function of the ciliary muscle[30,31]. The findings of this study agree with those obtained using the aforementioned evidence (Figure 5). In particular, a change in spherical aberration was identified with increases in stimulus vergences. However, due to the inter-subject variability obtained from the mean of all subjects, no additional tendency from that previously described in the literature was uncovered.

In summary, no significant differences were found in the accommodation responses for all of the conditions and stimulus vergences considered. This may be due to the youth of the subjects' eyes and their normal levels of amplitude of accommodation corresponding to their ages. Future work should include larger reading periods as well as larger samples of participants with wide age ranges to permit comparisons with the results obtained in this study.

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