Published in final edited form as:
Ergonomics. 2010 July ; 53(7): 892–903. doi:10.1080/00140139.2010.489968.

Effects of Age on Dynamic Accommodation

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Abstract

Visual accommodation plays a critical role in one's visual perception and activities of daily living. Age-related accommodation loss poses an increased risk to older adults' safety and independence. Although extensive effort has been made towards understanding the effect of age on steady-state accommodation, dynamic aspects of accommodation is still unknown. A study was therefore conducted to investigate age-related dynamic accommodative characteristics utilizing a modified autorefractor. Ten individuals from each of three age groups (i.e., younger group: 20 to 29 years old, middle-aged group: 40 to 49 years old, and older group: 60 to 69 years old) were recruited and their dynamic accommodation responses were examined. The laboratory experiment was designed to assess dynamic accommodation associated with an abrupt change from a constant far target (400 cm, 50 cd/m^2) to a near target (70 cm, 100 cd/m^2 or 20 cd/m^2), which aimed to simulate car dashboard reading behavior while driving. The results of the study indicated that age and target intensity both had a significant impact on dynamic accommodation. These effects were attributed to both the age-related physiological limitation of the eye as well as to central neural processing delay. A method of measuring dynamic accommodation and the implications of the study are discussed.

Keywords

Vision; Aging; Dynamic Accommodation; Autorefractor; Light Intensity; Accommodation

INTRODUCTION

Age distribution and mean age are undergoing a rapid and significant change worldwide. As people age, their abilities to see, hear, move, and process information all deteriorate. Studies suggest that increasing age has an adverse effect on various human capabilities, including visual and auditory perception (e.g., Shi *et al.* 2008, Casali 2006), mobility (e.g., Lockhart *et al.* 2005), and mental functionality (e.g., Denney and Palmer 1981). This paper focuses on the effects of age on visual perception as relates to dynamic visual accommodation.

One of the most frequently cited age-related visual deteriorations is the decline of the accommodative ability. Accommodation is the ability of the eye to automatically change its focus from one distance to that of another. The accommodative system is controlled by the crystalline lens which adjusts its curvature and shape so as to create a proper optical power of the eye to provide a clear retinal image of objects at various distances. The accuracy of

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this process determines how much information is extractable from visual stimulation and is therefore essential to virtually every visual task and the processing of visual information. However, the accommodative ability changes greatly due to the age-related changes of the eye, including a decrease in the elasticity of the lens and the degeneration of the Zonular fibers and the ciliary muscles surrounding the lens (Glasser and Campbell 1998). With the advancing of age, the lens hardens (Gullstrand 1909), the tension of the Zonular fibers declines (Weale 1962), and the activity of the ciliary muscles decreases (Duane 1922). As a result, it has been documented that aging leads to presbyopia, which is the continuous loss of the ability of the eye to change its focus on objects at close distances. Specifically, the nearest point a middle-aged person can focus on retrogresses to about 1 meter away from the eye, compared with younger counterparts who can focus on objects as close as 10–20 centimeters away from the eye (Mordi and Ciuffreda 1998).

A number of studies have investigated the age-related steady-state accommodation, particularly the amplitude of static accommodation, which is defined by the nearest and farthest points the eye can focus on statically (Koretz *et al.* 1989, Ramsdale and Charman 1989, Glasser and Campbell 1998, Mordi and Ciuffreda 1998). This measure however does not provide information regarding the transient nature of dynamic viewing. Due to the lack of studies on dynamic accommodation, the time varying aspects of the age-related accommodation loss are not fully understood. Although a recent study conducted by Mordi and Ciuffreda (2004) covered some of the dynamic aspects of accommodation and presbyopia (i.e., the microfluctuations of the accommodation response), their investigation focused mainly on the biomechanical aspects of the lens instead of the dynamic characteristics of the accommodation process. Some other attempts included Sun *et al.* (1988) and Ciuffreda *et al.* (2000), both of which aimed to find the relationship between age and the time taken by the eye to start accommodation (i.e., central neural processing delay as measured by the reaction time). However, Sun *et al.* (1988) failed to find any evidence for an increase in the reaction time with age, while Ciuffreda *et al.* (2000) found a slight increase of the reaction time at a rate of 2.5 ms per year under similar test conditions. The reasons for the mixed findings may be ascribed to: 1) the instrument being unable to record time dependent characteristics of dynamic accommodation, and 2) the manual detection of the onset/offset of dynamic accommodation. As the measure of accommodation poses a high demand on the capability of the equipment and the handler, some of the instruments have shown their limitations on measuring dynamic accommodation (mainly due to vulnerability to eye and head movements, and to pupil diameters), and through manual selection of the onset/offset point of dynamic accommodation - which may result in failure to correctly determine these critical points and thus restrict the comparability of different studies (Wolffsohn *et al.* 2001Sun *et al.* 1988, Ciuffreda *et al.* 2000, Mordi and Ciuffreda 2004)). Hence, the age-related effects of dynamic accommodative characteristics remain unresolved. In order to provide a better understanding of the age-related dynamic accommodation process, the present study used a more reliable instrument (the Shin-Nippon ® SRW 5000 autorefractor, Wolffsohn *et al.* 2001) to record the time series data of dynamic accommodation, as well as a replicable mathematical technique for robust data processing.

Moreover, as it is light that transmits external stimuli which trigger the accommodation process (Hung *et al.* 2002), a full investigation of the dynamic aspects of accommodation has to consider both the effect of age (intrinsic factor) and the effect of lighting (extrinsic factor). Among different aspects of light (e.g., intensity, chromaticity, and duration), this paper focuses on the effect of light intensity on the age-related accommodation loss. This is because the intensity of light directly influences the accommodation process (Johnson 1976, Rosenfield 1993, Arumi *et al.* 1997, Jackson *et al.* 1999), and the majority of the efforts so far were dedicated to the study of the static aspects of accommodation without inclusion of the age effect.

In order to provide a better understanding of the effect of age on the dynamic accommodation process, a study was therefore conducted to investigate the dynamic accommodative characteristics of the eye under different lighting conditions. It was hypothesized that the advancing of age and varying light intensity of the visual target would lead to the change of one's dynamic accommodative performance due to accommodation-related physiological limitations of the aging eye as well as central neural processing delay.

METHODS

Participants

Thirty participants were recruited for the study, ten from each of three age groups: younger group (20 to 29 years old, mean age = 24.1, s.d. = 3.22), middle-aged group (40 to 49 years old, mean age = 45.4, s.d. = 3.13), and older group (60 to 69 years old, mean age = 64.9, s.d. = 2.91). Informed consent was approved by the Institutional Review Board (IRB) of Virginia Tech and was signed by all of the participants. The participants did not have any eye disease or eye surgery and had normal vision in at least one of the eyes (20/20, corrected vision was acceptable only if contact lenses were worn). Static visual acuity and standard color blindness test (via a Bausch & Lomb ® Vision Tester) and static contrast sensitivity test (via a Vistech ® Contrast Sensitivity Chart) were conducted as screening tests to ensure that each participant met the criteria of normal vision.

The number of participants in each age group was estimated based on the published data of dynamic accommodation (Sun *et al.* 1988, Ciuffreda *et al.* 2000, Mordi and Ciuffreda 2004) to ensure that the sample size was large enough to detect differences in accommodation among younger, middle-aged, and older individuals with high probability (power>0.70).

Experiment Arrangement

To assess the dynamic accommodative capabilities, a mirror machine (figure 1) was used to automatically trigger the eye-focus from a far target (4m away from the eyes) to a near target (Maltese cross (figure 2) at 70 cm away from the eyes). The choices of 4 m (0.25 Diopters (D)) and 0.7 m (1.5 D) were based on the normal range of the focal point of the eyes when a driver, for example, is looking forward (i.e., 0 D) or reading a display on the dashboard while driving (i.e., 1.5 D) (Atsumi *et al.* 2004). The distance of 4m (0.25 D) was chosen to facilitate and represent a far target without having to place the far target at an infinite distance (0 D).

The room was dark (i.e., no ambient lighting except for the luminaries from the targets-scotopic - 5 lux). A fixation board, which was part of the the Shin-Nippon ® SRW-5000 autorefractor equipment (figure 2a), was placed on a black wall 4 m away from the participant's eyes and acted as a constant far target with a fixed luminance level of 50 cd/m^2. The Maltese cross (near target) was presented in two different light intensities (figure 2b). In order to trigger accommodation at different light intensities, the Maltese cross was displayed by a laptop with two light intensity levels: 100 cd/m^2 and 20 cd/m^2 (Lockhart et al., 2006).

Test Protocols

Before starting the formal session, each participant was familiarized with the layout of the apparatus, and the test procedures that is, the change from the far target to the near target triggered by the mirror machine was explained). Encouragements were given to the participants when high quality records were produced (i.e., clear shift of eye-focus from the far to the near targets), and the participants were discouraged from blinking during the recording. The formal testing began after completing five training trials of focusing on targets. Training trials consisted of participants practicing the shifting of the eye focus from

a far target to a near target. Presentation of target intensity levels was randomized and dynamic accommodation was assessed twice in each light condition. A one-minute break was given to the participants after each light condition.

Measure of Dynamic Accommodation

After accommodation was triggered, the modified Shin-Nippon ® SRW-5000 autorefractor was used to monitor the dynamic accommodative status. The original use of the autorefractor was to measure refractive errors of the human eye by projecting a measurement ring using the infrared light on to the observer's eye and measuring the refracted image by moving the Badal lens laterally to find the optimal focus distance of the ring image on the retina. As the size and shape of the ring image is determined by different eye conditions, the measure of the ring image provides the refractive prescriptions of the eye.

A brief description of the linear relationship between the movement of the Badal lens and the spherical refractive error is further provided to explain the dynamic accommodation measure. Given a normal (emmetropic) eye (Figure 3, bottom image) with D_0 total refractive power when looking at infinity, the Badal lens is located at a position where the measurement ring is projected accurately on the retina, and the refractive prescriptions for this eye are zero spherical error (0 diopter) and zero cylindrical error. At this position, there is a relationship between β_1 and β_2, as shown in Figure 3, and they are equal due to the symmetry of the ring image. As a result, tan (β_1) = tan (β_2), and $L/(1/F) = a/\gamma_0$, where L is the radius of the ring signal before entering the Badal lens, F is the power of the Badal lens, a is the radius of the ring signal before entering the polarized filter, and γ_0 is the distance between the focal point of the Badal lens and the polarized filter. Thus, $L/(1/F) = a/\gamma 0$, and $a = L*F*\gamma 0$, which is also the radius value for the ring signal before entering the cornea.

Since the normal eye has D_0 total refractive power, the distance between the cornea and the retina should be approximately $1/D_0$. If the normal eye becomes ametropic (e.g. myopic or hyperopic), the eye will have a certain value of spherical error as well as cylindrical error. Assuming there is no irregularity in terms of the curvature of the cornea, the eye will only have spherical error (ΔD, Figure 3, top image), and the total refractive power of the eye becomes $D_0+\Delta D$. Since the purpose of the Badal lens is to make the measurement ring signal be refracted onto the retina, the lens will move $\Delta\gamma$ so as to make the ring signal be focused on the retina, which is $1/D_0$ away from the cornea, instead of on a point which is $1/(D_0+\Delta D)$ away from the cornea due to the unchanged position of the Badal lens. Because the size of the measurement ring image projected into the eye is very small (<2.9 mm) (Wolffsohn et al., 2001), it is assumed here that when entering the cornea, the measurement ring signal projected by the autorefractor has a fixed refractive index, no matter what size the ring is at that moment. As a result, $\alpha_1 = \alpha_2$, and $a = L*F*\gamma_0$, $a' = L*F*(\gamma_0+\Delta\gamma)$. Thus,

$$\tan(\alpha_1)=\frac{a}{1/(D_0+\Delta D)}=\frac{L^*F^*\gamma_0}{1/(D_0+\Delta D)} \quad (1)$$

$$\tan(\alpha_2)=\frac{a'}{1/D_0}=\frac{L^*F^*(\gamma_0+\Delta\gamma)}{1/D_0} \quad (2)$$

$$\tan(\alpha_1)=\tan(\alpha_2) \quad (3)$$

$$\Delta\gamma = \frac{\gamma_0}{D_0}\Delta D \quad (4)$$

According to equation 4, there is a linear relationship between the movement of the Badal lens (Δγ) and the spherical refractive error (ΔD).

In order to provide continuous time series data showing the dynamic accommodation, the "sales mode" menu of the autorefractor instrument was altered to set the "Ref. Led" from "Auto" to "On", which gave continuous illumination of the measurement ring and collection of the reflected ring image (Wolffsohn *et al.* 2001). The instrument sampled the reflected ring image at a frequency of 60 Hz, which was collected by a Pentium IV 2.40 GHz PC with a National Instruments (NI) PCI-1407 image acquisition card via the output panel of the autorefractor. The ring images were then analyzed by the threshold method to obtain the diameter of the ring using Lab VIEW 8.0 programming and NI Vision Module 8.0.1 software (National Instruments, Texas, USA). The diameter value was then converted into the spherical equivalent (SE) value (Wolffsohn *et al.* 2001) which, by definition, summarizes the refractive errors of the eye (i.e., SE = sphere refractive error + ½ cylinder refractive error). As accommodation is virtually the change of the optical power of the eye, the change of SE was used to imply the dynamic accommodative status (Wolffsohn *et al.* 2001).

Since the spherical equivalent value is linearly related to the calculated ring diameter (Wolffsohn *et al.* 2001), a conversion equation was created based on simultaneous static and dynamic accommodative measures of a model eye with an axial length that could be altered (Heine Ophthalmoscope Trainer Model Eye, Heine, Germany). The equation was then used to convert the ring diameter to the spherical equivalent value, which provided high (60 Hz) temporal resolution of the dynamic accommodation process to an accuracy of <0.001 D (Wolffsohn *et al.* 2001).

Data Processing

Dynamic aspects of accommodation have previously been assessed by various vision researchers (Sun *et al.* 1988, Chat and Edwards 2001, Mallen *et al.* 2001, Wolffsohn *et al.* 2001, Heron *et al.* 2002, Rucker and Kruger 2004). While most of the studies recorded the accommodative status at fairly high resolution and sampling frequency, no agreement has been reached on how to process the raw data. The most commonly used method is via manual visual selection of the critical points during accommodation processes (i.e., the onset and offset of the accommodation) (Heron *et al.* 2002, Rucker and Kruger 2004). The deficiency of manual selection is that it provides unreliable detection of the critical points which prevents comparison between the results of the various studies. Thus, in order to overcome the weakness of manual selection, a more robust mathematical technique was implemented to process the raw data. This procedure facilitated objective detection of the critical points (which are shown in figure 4).

Specifically, a 4th order Savitzky-Golay filter was applied to the raw data to smooth the data (using a sliding window (2*60+1 points)). After obtaining the smoothed data, the onset and offset of accommodation was determined mathematically via a velocity curve. The speed of the focus of the eye during accommodation was calculated by dividing the differences between one preceding and one succeeding Spherical Equivalent (SE) value by the time interval between them (i.e., instantaneous focal velocity: 2*1/60s)). The lower graphs in figure 4 illustrate the velocity curves based on the smoothed data, which were further

smoothed by another 4th order Savitzky-Golay filter with a sliding window with fewer (2*20+1) points.

The accommodation process was characterized by four parameters: 1) the magnitude of accommodation (MOA), 2) the reaction time (RT), 3) the response time index (RTI), and 4) the peak velocity (PV). MOA indicates whether the eye can completely switch its focus from the far target to the near target, and is defined as the difference of the average Spherical Equivalent values between the two steady-state focus levels before and after accommodation. RT is the time the eye takes to start the accommodation process, and is defined as the time interval between the known instant of stimulus change (recorded via a synchronization function in LabVIEW) and the time at which the response begins to change from the initial steady-state level (i.e., the onset of accommodation, which is determined by the last local minimum velocity before PV). RTI represents a standardized measure of response time of accommodation over a unit distance (meter), and is calculated by dividing the time (between the onset of accommodation and the offset of accommodation which is determined by the first local minimum velocity after PV) by the focal distance covered during that time period between onset and offset points. From the velocity curve, PV denotes the maximum velocity at which the eye changes the focus.

Data Analysis

This study was a 3(age group, between-subjects) by 2(target intensity, within-subject) mixed-factor design. A two-way mixed-factor repeated-measure MANOVA was first conducted to assess the global effects of age, target intensity, and their interactions on the dynamic accommodative performances. Subsequent univariate mixed-factor ANOVAs were performed to ascertain the effects of the each dependent variables (i.e., MOA, RT, RTI, and PV).

RESULTS

In general, the study indicated that age and target intensity affected accommodation processes significantly (tables 1 and 2). Aligned with the well-documented findings of the age-related loss of the static amplitude of accommodation (Glasser and Campbell 1998,Mordi and Ciuffreda 1998), MOA decreased with greater age (table 1). As the accommodative demand (i.e., from 0.25 D to 1.5 D) was within the younger and middle-aged participants' accommodative capability but beyond that of older participants, a more remarkable decline of MOA was found in the results of the older adults' accommodative performance. In terms of the dynamic characteristics (table 1), older adults exhibited greater delay in time to start and finish accommodation (RT and RTI) and lower speed of accommodation (PV) as compared to their younger and middle-aged counterparts. The ANOVA tests (table 2) further indicated that there was statistically significant age effect ($p<0.05$) in each of the dependent variables.

In addition to the age effect, the study also found an effect of light intensity on dynamic accommodation (table 1 and 2). The results oare not only aligned with those of previous studies regarding the amplitude of accommodation under low light intensities (Johnson 1976,Rosenfield 1993,Arumi *et al.* 1997,Jackson *et al.* 1999), but also indicate an adverse effect of low light intensity on dynamic accommodative processes for all three age groups. Statistically significant differences ($p<0.05$) due to light intensity were found in each of the dependent variables for all of the age groups. The mean values shown in the table 1 consistently demonstrated that with decreased light intensity of the target, the focus mechanism of the eye became reluctant to the stimulus for accommodation (with larger RT and RTI, and smaller PV and Time%).

DISCUSSION

The Effect of Age on Dynamic Accommodation

The effect of age on dynamic accommodation was demonstrated in this study. Clearly, with aging, dynamic accommodative characteristics deteriorate (i.e., decreased magnitude of accommodation, prolonged reaction time, response time, and total accommodation time, and reduced peak velocity). An apparent explanation is the physiological changes of the eye, including increased lenticular hardness and decreased ciliary muscular tension. While the literature suggests that these changes can be considered as a major contributing factor to the age-related accommodation loss (Donders 1864, Duane 1912, Hofstetter 1965, Ramsdale and Charman 1989, Mordi and Ciuffreda 1998), it is further speculated that the increased reaction time for the accommodation response is likely not primarily due to physiological limitations of the eye, or to peripheral neuromuscular transmission delays, but rather to a delay in central higher-order neural processing time. Specifically, neurons with a signal proportional to viewing distance have been recorded in the mesencephalic reticular formation of the rhesus monkey, just dorsal and lateral to the oculomotor nucleus (Mays 1984, Judge and Cumming 1986). Similarly, an accessory oculomotor nucleus was also found near the oculomotor nucleus in humans. This accessory parasympathetic cranial nerve nucleus of the oculomotor nerve is called the Edinger-Westphal nucleus, which supplies preganglionic parasympathetic fibers to the eye, constricting the pupil and accommodating the lens (Jampel and Mindel 1967, Kourouyan and Horton 1997). It has been found that aging may have an adverse effect on the performance of this nucleus (Jampel and Mindel 1967, Ciuffreda *et al.* 2000), which may therefore have contributed to the age-related accommodation loss recorded in the current study. In other words, the effect of age on the dynamic accommodative performance may be viewed as a combination of the effects of aging on the biomechanical structure of the eye and on the neurons involved in human visual perception.

Another interesting finding on the effect of age on dynamic accommodation is that the variances of MOA was relatively similar among the three age groups, while those of RT and RTI were inflated with aging, especially between the middle-aged group and the older-aged group (table 1). This may suggest that the participants within each age group had similar performance on *how much* they could accommodate (i.e., MOA), but that the older group had larger variance in *how long* (i.e., RT and RTI) it took them to achieve a relatively similar performance in MOA. The larger variances found in RT and RTI for the older group were consistent with larger variances of performance in older age groups found in previous studies of the age-related accommodation loss (Duane 1912,Hofstetter 1965,Ramsdale and Charman 1989). On the other hand, the similar variances found in MOA might be ascribed to test protocols, in that each participant was asked to accommodate as much as possible without a set end time. In other words, the study suggested that older adults with healthy eyes could accommodate to a similar extent but in a different duration. Future research should elucidate the causal factor on the time varying accommodation characteristics of the elderly population.

The Effect of Light Intensity on Dynamic Accommodation

While the age-related accommodation loss may be considered to be largely due to the biomechanical changes of the eye (specifically, of the crystalline lens, the ciliary muscle and the Zonular attachments) and to a delay in central processing time, the effect of light intensity on accommodation is mainly a result of the neural characteristics of the eye, especially the cone photoreceptors on the retina.

Information on defocus carried by light is transmitted via cone signals, bipolar cells, and retinal ganglion cells to the LGN (lateral geniculate nucleus). This pathway is often referred to as the luminance pathway and it is a weighted sum of L-, M- and S-cone contributions (Rucker and Kruger 2004). As the firing rate of cones declines with diminishing light intensity (Roorda and Williams 1999, Schiffman 2005), cones lose their sensitivity to images of different luminance contrasts. Consequently, less amount of accommodation stimulus is collected by cones and then transmitted to the visual cortex via the luminance pathway. Hence, reduced accommodative power associated with diminishing intensity of light has been observed in previous studies (Johnson 1976, Rosenfield 1993, Jackson *et al.* 1999). The decreased dynamic accommodative performance found in the present study also supported this argument (table 1). However, as this study was the first one to include the effect of light intensity on the dynamic aspects of accommodation, only the reaction time under the dark condition (i.e., 20 cd/m^2) may be compared with other published results (Heron *et al.* (2002) with a target of 35 cd/m^2 used; Mordi and Ciuffreda 2004, a target of 25 cd/m^2 used). The reaction time from the present study (395 ± 121ms) was similar to those from the other studies in the dark condition (340 ms, Heron *et al.* 2002; 325 ~ 530 ms, Mordi and Ciuffreda 2004).

The Interaction Effect between Age and Light Intensity

The advancing of age has an adverse effect on the photoreceptors on the retina. That is, when one gets older, the photoreceptors start to degenerate and lose their functionality. The loss of rods begins first and is then followed by the loss of cones. Due to the accelerated loss of cones at older ages (Curcio *et al.* 1996), older adults, compared with younger and middle-aged counterparts, were expected to exhibit a more remarkable decline of the dynamic accommodative performance, and this decline was expected to differ at different lighting conditions due to the light-related sensitivity of cones. Specifically, table 1 indicated that a larger decline in dynamic accommodative performance was found between the middle-aged and older group than that between the younger and middle-aged group. This difference was more apparent under the daytime lighting conditions than under the nighttime lighting conditions. This finding could be explained by the age-related cone degeneration and the cone-light relationship. That is, under the daytime lighting conditions, the sensitivity of cones remains and the age-related cone degeneration may contribute to the further decline of dynamic accommodative performance during the daytime condition. On the other hand, under the nighttime lighting conditions, the sensitivity of cones declines and the age-related cone degeneration may not have as much impact as it is supposed to have when the sensitivity of cones is guaranteed by sufficient light intensity. In this sense, the results of the present study indicated the cone-related neural processing deficit with aging and its impact on dynamic accommodation. Although implicated, further study is needed to quantify the interaction between age and cone degeneration on dynamic accommodation. It should be noted that, since all the participants were screened to ensure the healthiness of their eyes to facilitate the measure of dynamic accommodation via the autorefractor (Wolffsohn *et al.* 2001), age-related ocular opacity, which may affect light transmittance, was considered to have minimal effect on the results of the present study. Future research might usefully include this factor and assess its impact on dynamic accommodation.

Measure of Dynamic Accommodation

In order to measure accommodation, a mirror machine system (figure 1) was designed to create an abrupt change of targets at different distances. The system included a rail system (track) to position targets of different characteristics at different distances or to move them along the track. So, this system could be utilized to access a variety of accommodative performance, including abrupt far-to-near/near-to-far accommodation, continuous far-to-near/near-to-far accommodation, and dark focus (defined by the focal point of the eye in

total darkness). Under each accommodation scenario, the dynamic/temporal aspects of accommodation can be evaluated via the use of the modified autorefractor and LabVIEW image analysis, which was first created by Wolffsohn *et al.* (2001) and was proven to be appropriate in the present study.

Unlike the previous published studies of dynamic accommodation (Sun *et al.* 1988, Ciuffreda *et al.* 2000, Mordi and Ciuffreda 2004), the present study was facilitated by the development of a replicable mathematical data processing technique to robustly analyze accommodative performances. Utilizing the Savitzky-Golay filtering technique, noise from high-frequency movement artifacts was removed from the raw data while preserving abrupt level changes, which led to a clear accommodation response. After converting the smoothed accommodation response to a velocity curve, the onset and offset of an accommodation were uniquely identified, eliminating the use of subjective visual detection. As Savitzky-Golay filtering utilizes polynomial regression to find the best-fit curve at each original data point by considering the surrounding data (i.e., the range of the data is controlled by the size of the sliding window), a larger window size (data points recorded in 2 seconds) was used to remove high-frequency movement artifacts from the raw data. Furthermore, as the velocity data was derived from the filtered data, a narrower sliding window (data points recorded in 0.67 seconds) was necessary for further smoothing. Both of the sliding windows provided consistent data processing in the present study, and resulted in dynamic accommodative characteristics that were comparable with published results.

Comparison of the Results with the Literature

Early studies using fairly crude reaction-time methods and step stimuli (Allen 1956, Temme and Morris 1989) found that overall response times were longer for older subjects. Although Sun *et al.* (1988), using an infra-red optometer and a stimulus change from 1 to 4 D, suggested that the reaction time showed little change with age, age-related deterioration in dynamic accommodation was found by Schaeffel *et al.* (1993) via photoretinoscopy, Beers and van der Heijde (1996) via ultra-sound, and Ciuffreda *et al.* (2000) via an optometer. Nevertheless, no agreement on the normal range of the dynamic characteristics of accommodation has previously been reached. Consequently, only a portion of the results could be compared with the literature.

The age-related changes of the magnitude of accommodation (MOA) found in the present study agreed with the normal range of the amplitude of accommodation found in the literature (table 3). As the unit of Diopter is derived from the reciprocal of a distance of 1 m, an amplitude of 9 Diopters indicates that the eye can accommodate from infinity (1/0 = infinity) to about 10 cm (1/9 = 0.11). As such, the normal range of the amplitude of accommodation found in related research (table 3) suggests that both younger and middle-aged adults can accommodate at least from 4 m to 70 cm, which is consistent with the results of the present study. As for the results of the older group, their magnitude of accommodation was compared directly with the normal range of the amplitude of accommodation for the elderly, in that the stimulus for accommodation in the present study was expected to trigger the maximum amount of the accommodative ability for the older participants. Table 3 indicates that the results of the age-related changes of the magnitude of accommodation found in the present study were consistent with the literature.

The reaction time was also in agreement with those found in previous investigations (table 4). In spite of a variety of sample sizes and age ranges used in the other studies (Sun *et al.* 1988,Ciuffreda *et al.* 2000,Heron *et al.* 2002), table 4 suggests that the reaction time measured in the present study was fairly close to those documented in the literature.

Implications and Limitations

The study was expected to clarify the effects of age and light intensity on dynamic accommodation. The literature (Heath 1956, Phillips and Stark 1977, Charman and Tucker 1978, Bobier *et al.* 1992, Hung *et al.* 2002) suggests that the stimulus for accommodation is transmitted by light to the retina via refraction at the cornea and the lens, and the retina conveys the information to the visual cortex of the brain. Afterwards, the brain sends out a signal to the lens and its surrounding muscles to trigger accommodation. As the lens and the photoreceptors on the retina are both affected by the age-related changes of the eye, the completion of the study could help uncover the temporal and spatial characteristics of the accommodative ability of people at different ages and under different lighting conditions. Specifically, the results of the study not only supported the use of the modified autorefractor to study the dynamic accommodative characteristics of the eye under various lighting conditions, but also provided better understanding of the effects of age and light intensity on the accommodative ability of the eye. Future study will include various light (optical) parameters associated with different age groups to provide a more reliable assessment of dynamic accommodative characteristics.

Within the confines of the experimental design, the authors believe that the findings can provide better insight into the accommodative ability associated with aging, which can be applied to areas such as virtual reality and visual display terminal design. Specifically, with the knowledge of the dynamic accommodative characteristics and the factors affecting them, the movement of the focus of the eye can be modeled quantitatively to depict how the eye actually changes its focus during accommodation, given the age of the person and the lighting conditions that are within the scope of the study. In other words, it may be possible to allow the virtual reality technology to project an image that is always located at the focal point of the eye during accommodation, resulting in clear resolution of the image. As older adults are found to have less accommodative power and longer accommodation time, the use of Virtual Reality and the knowledge of the focal point of the eye would benefit the older population the most. Additionally, with the incorporation of other aspects of light (e.g., light color spectrum, light duration, etc), a practical guideline describing optimal lighting conditions for visual display devices could be created to facilitate visual display terminal design and to enhance the visual performance of the aging population.

In spite of these implications, however, the accommodation process tested was limited to a far to near accommodation paradigm wherein each participant was asked to switch focus from a far target to a near target as quickly as possible. This arrangement was expected to simulate a driver reading dashboard information while driving, which is also a far to near accommodation with time pressure. Future study will further explore the accommodative performances of near-to-far target acquisition similar to when a driver accommodates from looking at the dashboard to reading a distant target (e.g., a road sign or nearby traffic). In this sense, realistic targets and proper levels of target intensity must first be discovered.

Finally, the study was confined to an abrupt change of the stimulus for accommodation with the exclusion of vergence-related accommodation. As the modified autorefractor has been shown to be capable of capturing sinusoidal accommodation changes (Wolffsohn *et al.* 2001), the study of dynamic accommodation with a continuous stimulus would help evaluate the effect of eye-fatigue on accommodation. Since the study assured the alignment of the tested eye with the center of the far and near targets, vergence of the eyes was minimized in the study. In other words, the experimental paradigm was designed to assess the dynamic aspects of a blur-driven accommodation with an abrupt change of the stimulus. Future study of vergence accommodation can provide us with a more comprehensive understanding of dynamic accommodation as it takes into consideration the saccades (the actual movement of the eye).

Conclusions

In order to provide a better understanding of the age-related dynamic accommodation process, the present study utilized a more reliable instrument to record the time varying aspects of dynamic accommodation. A replicable mathematical technique was also applied to the data processing for objectivity. The results suggested three possible sources of age-related dynamic accommodation loss - biomechanical inflexibility of accommodation-related ocular structures, increased central neural processing time, and decreased sensitivity of the cone photoreceptors. It is the authors' hope that this method will enable us to compare results across different studies related to dynamic accommodation.

Statement of Relevance

The results of the study indicated that age and target intensity both had a significant impact on dynamic accommodation. These effects were attributed to age-related physiological limitation of the eye as well as central neural processing delay, and to decreased sensitivity of the cone photoreceptors. To enhance the visual performance of the aging population involving dynamic accommodation, target distance and target light intensity should be carefully evaluated to facilitate effective viewing.

Acknowledgments

We would like to thank Mr. Bunji Atsumi of Toyota Motor Corporation, Japan, for his assistance and for his love of vision research. Thanks for sharing your vision Atsumi-san.

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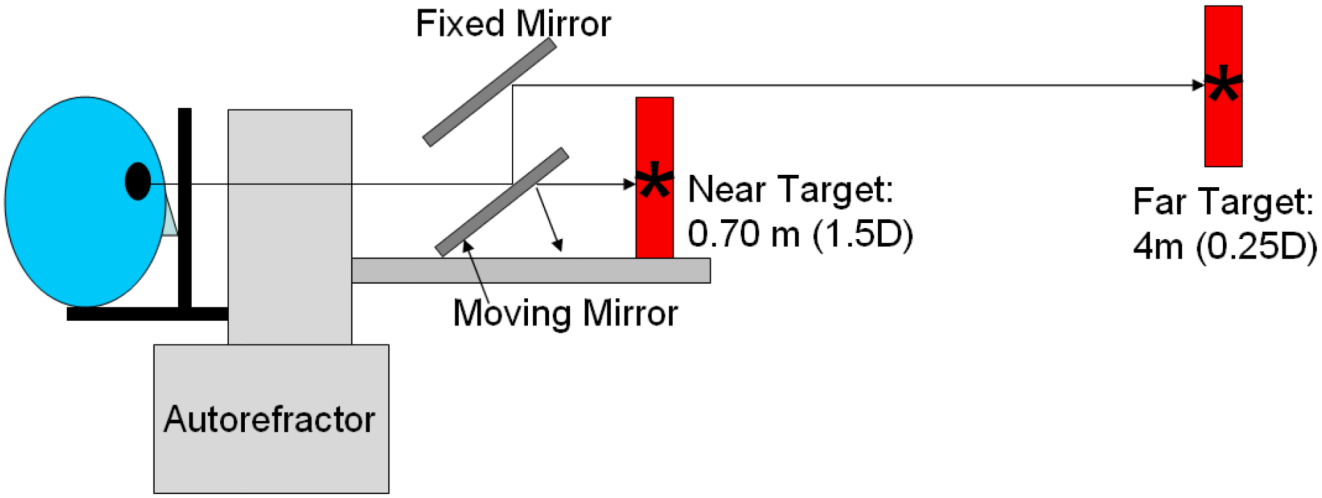

Figure 1.
The mirror machine

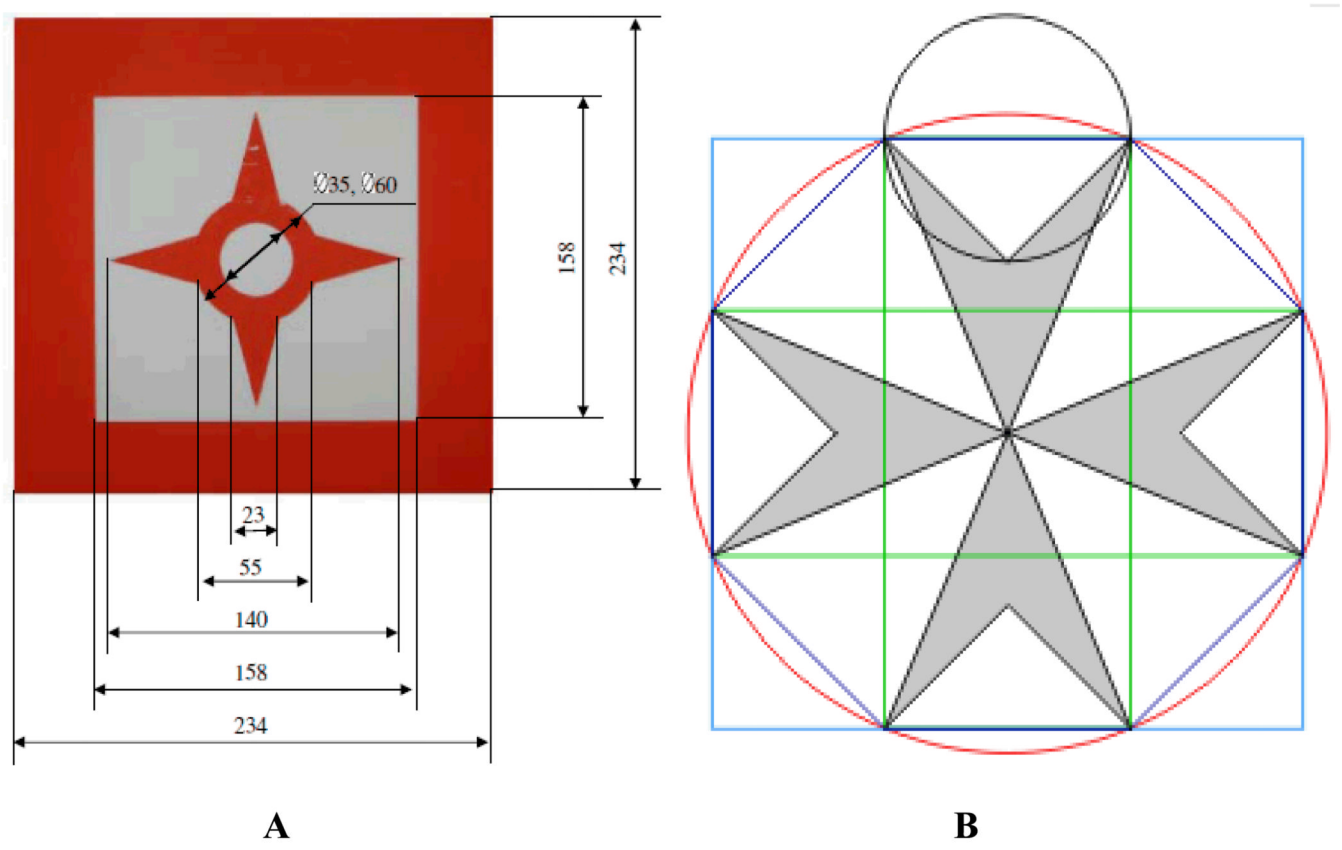

Figure 2.
The fixation board (dimensions in mm) - A, and the Maltese cross (the shadow area) - B.

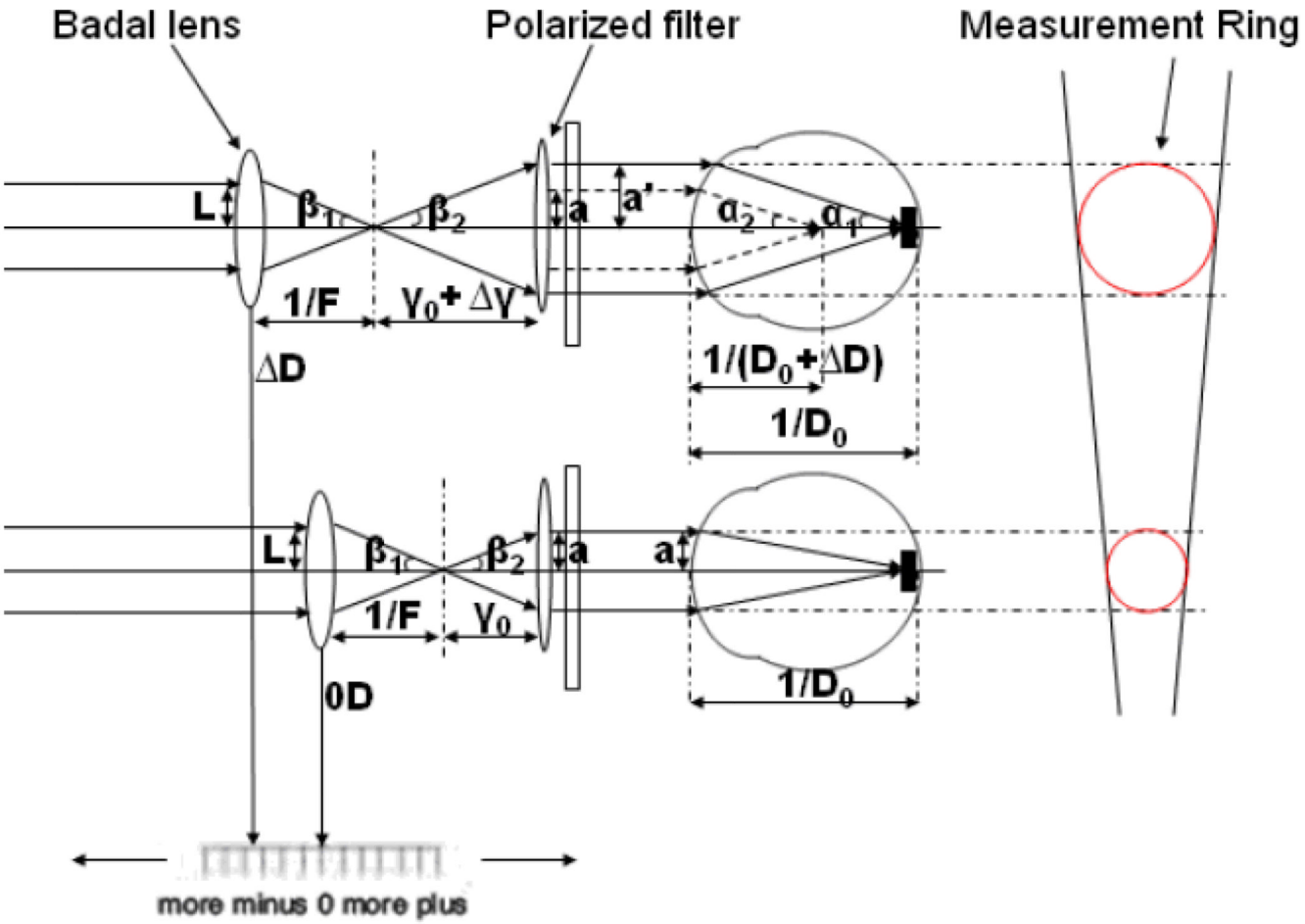

Figure 3.
The relationship between the Badal lens and the spherical refractive error.

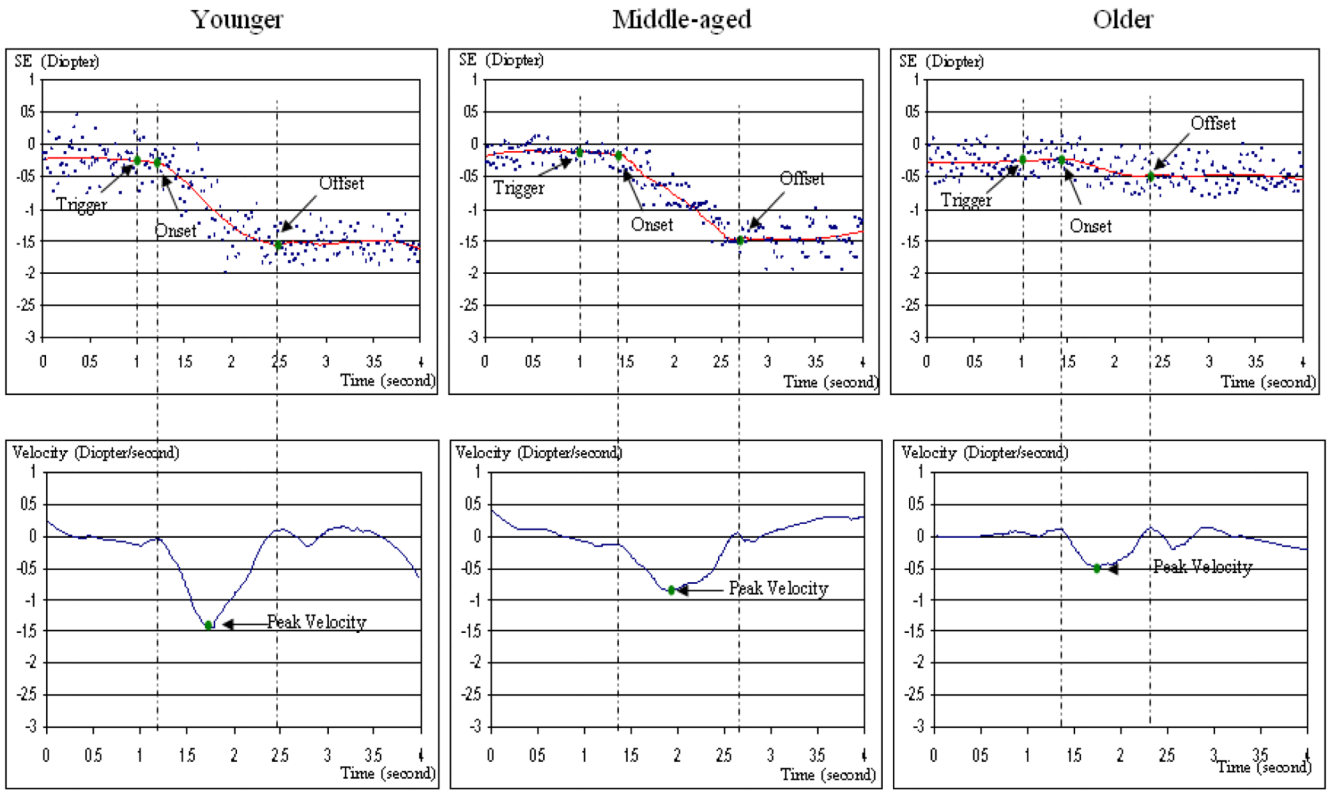

Figure 4.
Sample accommodation processes associated with different age groups, including the trigger, onset and offset points as defined by their velocity curves (SE = Spherical Equivalent). The fitted curves in the three upper graphs represent the time varying nature of accommodation from a far target to a near target as measured by SE.

Table 1

Results of each dynamic accommodative characteristic by target intensity and age group (mean ± standard deviation)

Target Intensity/ Age Group		MOA (Diopter)	RT (ms)	RTI (ms/m)	PV (Diopter/sec)
Bright	Young	1.271 ± 0.138	224 ± 30	318 ± 41	1.878 ± 0.625
	Middle	1.239 ± 0.121	350 ± 40	356 ± 34	1.127 ± 0.658
	Old	0.244 ± 0.121	423 ± 55	438 ± 107	0.550 ± 0.273
Dark	Young	1.003 ± 0.171	252.304 ± 38.252	369 ± 39	1.568 ± 0.541
	Middle	0.771 ± 0.167	411.235 ± 48.038	421 ± 41	0.752 ± 0.412
	Old	0.165 ± 0.086	521.390 ± 59.509	442 ± 89	0.374 ± 0.198

Table 2

MANOVA and ANOVA results (Significant effects, $p<0.05$)

	MANOVA	**ANOVA**			
		MOA	**RT**	**RTI**	**PV**
Source	Prob > F	Prob > F	Prob > F	Prob > F	Prob > F
Age	**<.0001**	**<.0001**	**<.0001**	**0.0230**	**<.0001**
Intensity	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Age*Intensity	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0071**

Table 3

Comparison of MOA (mean ± SD) between the results of the present study and those in published literature

Age Group	Present Study MOV (Diopter)	Published Literature Amplitude of Accommodation (Diopter)	
Younger Group (20–29 years)	1.18 (able to accommodate from 4 m to 70 cm)	9 ± 2 * 10 ± 3.5 **	Both suggesting the ability to accommodate from 4 m to 70 cm
Middle-aged Group (40–49 years)	1.18 (able to accommodate from 4 m to 70 cm)	3.5 ± 2.5 * 5 ± 2 **	Both suggesting the ability to accommodate from 4 m to 70 cm
Older Group (60–69 years)	0.244 ± 0.121	0.3 ± 0.2 * 1 ± 0.5 **	

* Mordi and Ciuffreda, 1998

** Duane, 1912

Table 4

Comparison of RT (mean ± SD) between the results of the present study and those in published literature

Age Group	Present Study RT (ms)	Published Literature RT (ms)
Younger Group (20–29 years)	238 ± 37	340 ± 100* 300 – 500 ** avg. +2.5 / year increase in reaction time
Middle-aged Group (40–49 years)	381 ± 53	325 (average)***
Older Group (60–69 years)	472 ± 75	N/A

* Heron, *et al.*, 2002; 19 subjects; age: 18–49 years

** Ciuffreda, *et al.*, 2000; 72 subjects; age: 21–50 years

*** Sun, *et al.*, 1988; 6 subjects; age: 13–46 years