THE AGE-RELATED DYNAMIC ACCOMMODATIVE CHARACTERISTICS ASSOCIATED WITH LIGHT INTENSITY AND CHROMATICITY

BY

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(ABSTRACT)

Visual accommodation plays a critical role in one's visual perception and activities of daily living. The age-related accommodation loss poses a greater risk to older adults' safety and independence. Although extensive effort has been made to study the effects of aging on accommodation, the relationship between aging and the dynamic aspects of accommodation is still unknown. Furthermore, since light is the carrier of external stimuli for accommodation, it is of value to assess the influences of light on the age-related accommodation loss. Therefore, a study was conducted to investigate the age-related dynamic accommodative characteristics under various conditions of the intensity and chromaticity of light. To ascertain the effects of aging, 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. Laboratory experiments were designed to measure accommodation in a simulated condition where a person must alternate from viewing outside to reading the dashboard while driving. It was hypothesized that the advancing of age will lead to the deterioration of one's dynamic accommodative performance, and light of different intensities and chromaticities will interact with the effects of aging on accommodation.

The results of the study supported the above hypotheses. It was found that the advancing of age, the decrease of light intensity, and the change of light chromaticity all led to the alteration of one's dynamic accommodative performance. The present study concluded with a biomechanical and neural model elaborating the mechanism of an accommodation process within the scope of the study.

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ABBREVIATIONS

ANOVA	Analysis of variance
ATI	Accommodation time index
MANOVA	Multivariate analysis of variance
MOA	Magnitude of accommodation
PV	Peak velocity
RAT	Reaction time
RPT	Response time
RTI	Response time index
SD	Standard deviation
SE	Spherical Equivalent
Time%	Percentage of the response time to reach the peak velocity
TTA	Total time to accommodate
Tukey's HSD	Tukey's Honestly Significant Difference

1. INTRODUCTION

1.1 Rationale

The US population is aging. According to the US Census Bureau (2000), the median age increased from 32.9 years in 1990 to 35.3 years in 2000, reflecting a change in age distribution toward the older ages (U.S. Census 2000 Brief, C2KBR/01-12). In 2000, 35 million Americans were aged 65 years or over, which represented 12.4% of the total population, compared with only 4.1% aged over 64 years 100 years ago (Haegerstrom-Portnoy, 2005).

As people age, their ability to see, hear, move, and process information all deteriorates. Studies suggest that increasing age has an adverse effect on various human capabilities, including visual and auditory perception (e.g., Lockhart and Casali, 2004), mobility (e.g., Lockhart, et al. 2005), and mental functionality (e.g., Denney and Palmer, 1981). Since vision is the primary sensory channel responsible for up to 95% of driving-related inputs (Shinar and Schieber, 1991), the impairment in visual perception due to aging has been suggested as a likely factor contributing to the increased crash rates of older drivers (Shinar and Schieber, 1991). Hence, in order to improve the visual capability of the elderly, effort needs to be directed to understanding the characteristics of age-related visual deterioration.

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 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 this process determines how much information is extracted from visual stimulation and is therefore essential to virtually every visual task as well as the processing of visual information. However, the accommodative ability changes greatly with aging. It has been demonstrated that the amplitude of accommodation[1] declines significantly with the advancing of age (Donders, 1864, Duane, 1912, Hamasaki, et al., 1956, Hofstetter, 1965, Charman, 1989, Ramsdale and Charman, 1989, and Koretz, et al., 1989), which is mainly due to the age-related changes of the eye, including a decrease of the elasticity of the lens and the degeneration of the Zonular fibers and the ciliary muscles surrounding the lens (Glasser and Campbell, 1998). Studies suggest that for a middle-aged person, the nearest point he or she can focus on retrogresses to about 1 meter away from the eyes, compared with younger counterparts who can focus on objects as close as 20 centimeters away from the eyes (Mordi and Ciuffreda, 1998).

In spite of the well-documented, age-related loss of the amplitude of accommodation, it is not yet fully understood what other accommodative characteristics suffer from the age-related changes of the eye, especially in the dynamic domain (Mordi and Ciuffreda, 2004). As accommodation is a process which continuously changes the focus of the eye, the knowledge of how the focus changes during accommodation can lead to better understanding of the impact of the age-related accommodation loss on older people, and their daily activities. For example, based on Atsumi, et al.'s study (2004), Figure 1 illustrates the change of the optical power of the eye when one needs to read the dashboard information while driving. It suggests that, due to the change of visual distance between looking outside and reading the dashboard, the age-related accommodation loss may play a critical role in the reading performance and thus pose risks to driving. In other words, if the process of accommodation is longer for an older driver, which may be due to a delayed reaction to the stimuli for accommodation, he or she may spend more time to read the dashboard information. As a result, it may become riskier to drive because the reading task distracts attention from operating the vehicle. Moreover, if an older driver fails to accommodate properly due to the loss of the amplitude of accommodation, he or she may have difficulty in perceiving the information from the dashboard correctly, which may further increase the risks of accidents (Atsumi, et al., 2004).

[1] The amplitude of accommodation: the difference between the optical power at the nearest point and that at the farthest point the eye can focus on.

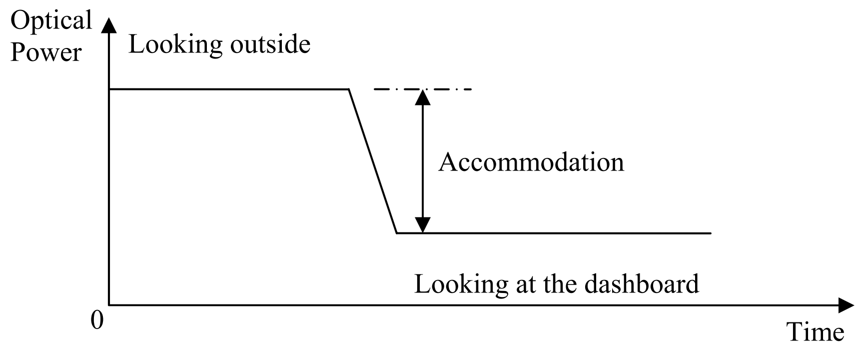


Figure 1: Change of the optical power when reading the dashboard during driving

Therefore, to elucidate the effects of aging on the accommodation process, a study was conducted to investigate the dynamic accommodative characteristics of the eye among younger, middle-aged, and older individuals, via the modified Shin-Nippon SRW-5000 autorefractor[2], under various conditions of the intensity and chromaticity[3] of light. The accommodation monitored was a complete accommodation process when one must switch abruptly his or her focus from far to near images, which aimed to simulate the accommodative behavior typically involved in daily life, similar to reading the dashboard while driving (Atsumi, et al., 2004). It was expected that by expanding to the dynamic domain of the process of accommodation, the effects of aging on one's accommodative ability could be better ascertained.

Additionally, along with the research on the effects of aging, the present study also explored how the accommodative ability was affected by another critical factor: light. It is important to consider the effects of light on accommodation, because light is the carrier of external stimuli which trigger accommodation (Hung, et al., 2002). In this view, the study of the effects of aging can provide information in regard to the intrinsic factors affecting accommodation, while the study of the effects of light can provide better understanding of the extrinsic factors of accommodation.

[2] Autorefractor: an infrared triggered open view computerized instrument designed to measure the refractive errors of the eye.
[3] Chromaticity: the quality of a color as determined by its dominant wavelength and purity.

Specifically, many studies have indicated that decreased light intensity or shorter light wavelength (i.e., bluish chromaticity) reduces the amplitude of accommodation and makes proper accommodation more difficult (Fincham, 1951, Johnson, 1976, Rosenfield, 1993, Arumi et al., 1997, Jackson, et al., 1999, Wilson, et al., 2002, Rucker and Kruger, 2004, Kruger, et al., 2005). In other words, the focus of the eye cannot be located as close as possible to the designated image if the image is dark or bluish instead of a bright or reddish one. The causes of such phenomena are usually ascribed to the longitudinal chromatic aberration[4] and the sensitivity of cones to light of different intensities and chromaticities (Johnson, 1976, Rucker and Kruger, 2004). Because of these effects, light of different intensities or chromaticities may create different stimuli for accommodation and thus may alter the patterns of accommodation (i.e., temporal and spatial). Hence, by assessing the dynamic accommodative performance, the knowledge of the effects of the intensity and chromaticity of light on accommodation can be expanded. The results may provide useful information in terms of how the age-related accommodation loss can be compensated for by using a certain lighting condition which may create the strongest stimulus for accommodation.

In summary, the present study aimed to investigate the dynamic accommodative characteristics of the eye with the consideration of the effects of aging, light intensity, and light chromaticity. It was hypothesized that aging will lead to the deterioration of the dynamic accommodative performance, and light of different intensities and chromaticities will change the age-related accommodation loss. By investigating these factors, the author believes that the age-related accommodation loss under different lighting conditions can be determined, and the results of the study can help better understand the age-related accommodation loss and benefit the aging population.

[4] Longitudinal chromatic aberration: the chromatic dispersion of light by the ocular media due to the different refractive indices for different wavelengths of light.

1.2 Research objectives

This study focused on investigating the intrinsic (i.e., the age-related changes of the eye) and extrinsic (i.e., light) factors associated with the dynamic accommodative performance of the eye by utilizing a newly developed method to continuously monitor the accommodation process. Specifically, the objectives of the study were:

1. To record dynamically a complete accommodation process of the eye via the modified Shin-Nippon SRW-5000 autorefractor;
2. To investigate the effects of aging on the dynamic accommodative performance;
3. To investigate the effects of the intensity of light on the dynamic accommodative performance;
4. To investigate the effects of the chromaticity of light on the dynamic accommodative performance;
5. To investigate the interactions among aging, light intensity, and light chromaticity on dynamic accommodation.

1.3 Hypotheses

The hypotheses of the study were: 1) the age-related changes of the eye will lead to the change of the dynamic accommodative performance; 2) light of different intensities will influence one's dynamic accommodative performance; 3) light of different chromaticities will result in different dynamic accommodative performances; and 4) light of different intensities and chromaticities will change the age-related accommodation loss. To test these hypotheses, multivariate analysis of variance (MANOVA) and subsequent univariate analysis of variance (ANOVA) were performed to assess whether there were statistically significant differences ($p < 0.05$) in the dynamic accommodative performance associated with different age groups, light intensities, light chromaticities, and their interactions.

1.4 Needs of the study

Upon the completion of the study, the results can provide a better understanding of the true mechanism of a dynamic accommodation process. The effects of aging, light intensity, and light chromaticity on dynamic accommodation may be applied to help improve older adults' visual performance and their quality of life. For example, if a certain combination of the intensity and chromaticity of light is found to be beneficial for different age groups in terms of their accommodative performances, the automotive industry may utilize these results to design information display devices to enhance the visual performance of drivers at different ages so as to improve driving safety.

As a matter of fact, statistically significant effects of aging, light intensity, and light chromaticity were found in the study, and three design guidelines for visual signal design were thereafter developed (see Section 5.4.3 Guidelines for visual signal design).

2. LITERATURE REVIEW

This literature review is divided into four sections. The first two sections introduce briefly the basics of the human eye and the accommodation process, which include the physiological structure of the eye, the refraction of light, the physiological changes of the eye during accommodation, and the measure of accommodation. The third section then discusses how the accommodation process is affected by aging. In the last section, literature is reviewed on the relationship between light reaching the eye and the accommodation process; specifically, the effects of the intensity and chromaticity of light on accommodation are discussed.

2.1 The basics of the eye

2.1.1 The physiological structure

The human eye is a finely-developed light receiving and processing machine. The major parts of this machine include the cornea, the aqueous humor, the iris diaphragm, the lens, the vitreous humor, the retina, and the optic nerve (Figure 2).

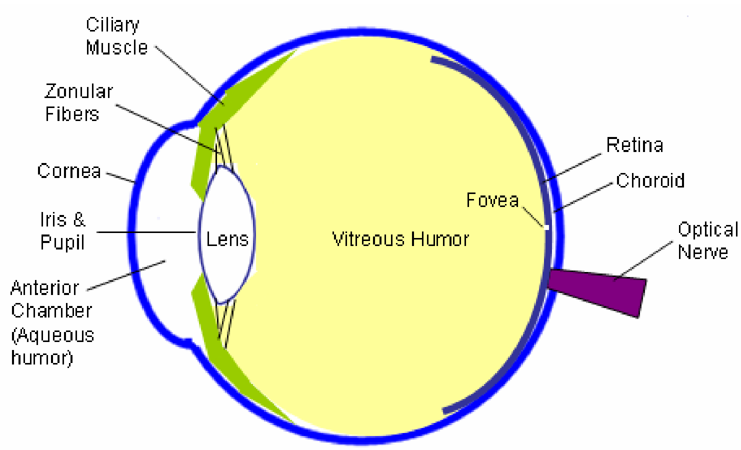


Figure 2: Schematic of the human eye

2.1.1.1 The cornea

The cornea is located at the most anterior surface of the eye with no blood vessel in its tissue (Cogan and Kinsey, 1942). It is mostly composed of water and collagen and is one of the most sensitive components in the eye. The center of the cornea is relatively thinner than the area at the periphery. The curvature of the cornea is responsible for up to two-thirds of the total optical power of the eye, while other components account for the rest of the optical power. Different from the crystalline lens, the cornea cannot change its curvature voluntarily, and thus its optical power is relatively fixed.

2.1.1.2 The aqueous humor

The aqueous humor of the eye is a fluid-like substance filling the anterior chamber between the cornea and the crystalline lens. This fluid is continually produced and exuded from the chamber to preserve a certain range of intraocular pressure (Troncoso, 1942). The aqueous humor has two roles in the functioning of the eye. First, it supports the cornea and helps it maintain a constant curvature. Second, it creates space for the movement of the crystalline lens. Specifically, it is known that whenever the crystalline lens changes its curvature, leading to the accommodation process, the anterior pole of the lens will move forward to the cornea, while the posterior pole remains fixed. During the movement of the cornea surface, the anterior chamber becomes shallower by exuding the aqueous humor.

2.1.1.3 The iris diaphragm

The iris diaphragm is located in the anterior chamber. The peripheral area of the diaphragm contains racially-different visible pigments of the eye, resulting in a colorful distinction across different races. The function of the iris diaphragm is to filter the light by only allowing the light to pass through its central area, called the pupil. The pupil can be adjusted to various diameters from approximately 2 to 8 mm (Davson, 1949, Wagman and Nathanson, 1942). As the pupil size changes, the amount of light entering the eye is changed.

2.1.1.4 The crystalline lens

The crystalline lens (Figure 3) is probably the finest piece of the eye. It is an elastic transparent structure possessing nothing but water and fat along with some degree of protein. The protein content is used to absorb the infrared and ultraviolet light that could damage the lens. In spite that the crystalline lens provides only a small refractive power (Moses, 1987), it is mainly the lens that makes it possible to see objects at different distances clearly without changing the location of the viewer. This process is called accommodation and is accomplished by the muscles surrounding the lens, namely the ciliary muscles and the Zonular fibers. When the muscles are highly relaxed, the lens will remain relatively flat and the eye can function properly for focusing on relatively distant objects. In order to look at closer objects, the muscles contract so that the lens becomes thicker and images of near objects can be focused correctly on the retina by the increased curvature of the lens. In general, people with normal eyes have the ability to accommodate objects from about 15 cm up to 6 meters (Duane, 1922).

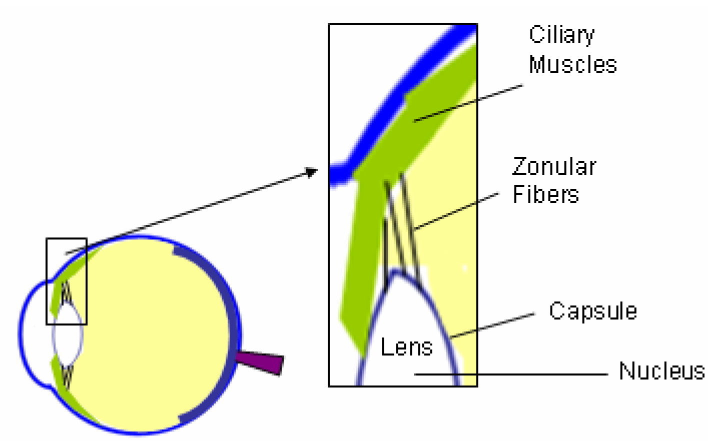


Figure 3: The crystalline lens of the eye

2.1.1.5 The vitreous humor

The posterior compartment of the eye contains a jelly-like fluid called the vitreous humor. The existence of the vitreous humor is to form the shape of the eye and to provide enough distance between the crystalline lens and the retina so that the lens can refract the light onto the retina. The vitreous humor occupies up to 80% of the eyeball, and virtually no light distortion is introduced in this area.

2.1.1.6 The retina

The retina is the innermost membrane in the eye. It lies along the posterior area of the eyeball. On the surface of the retina, there are two kinds of photoreceptors called rods and cones. Rods are normally responsible for sensing any moving targets and are found mostly at the area away from the center of the retina. Cones, on the other hand, are mostly found at the center of the retina and are heavily used for acuity perception. The center of the retina is called the foveal area and the center point of the area is the fovea, where lie more than 90% of the total cones (Schiffman, 2005). As a result, the eye has the highest resolution ability when images are refracted on the foveal area.

The photoreceptors on the retina extract the visual information carried by the refracted light, which is then collected by the retinal ganglion cells and transmitted to the brain via the optic nerve.

2.1.1.7 The optic nerve

The optic nerve is the connector between the eye and the brain. It starts from the retinal ganglion cells and ends in the lateral geniculate nucleus (LGN) from where information is relayed to the visual cortex.

2.1.2 The refraction of light (How the eye works)

The structure of the eye (Figure 2) is built on a single purpose: to focus light onto the retina. When light enters the eye, it will pass through the cornea and the aqueous humour, and reach the lens. Most of the light refraction occurs at the cornea which has a fixed curvature maintained by the aqueous humour. The iris, between the lens and the aqueous humour, is a ring-like area of muscle fibers colored by the iris pigment. The iris controls the amount of light finally reaching the retina by means of its central part, the pupil. The lens, behind the iris, is a convex disc which focuses light, through the vitreous humour, onto the retina by automatically adjusting its curvature, namely accommodation. After reaching the retina, the light will arouse the firing of the photoreceptors on the retina, most of which are located near the fovea. The chemical changes of these photosensitive cells will then be transmitted by the ganglion cells through the optic nerve to the visual cortex of the brain for processing and perceiving the light.

2.2 The basics of accommodation

Although visual perception is mainly achieved in the level of the visual cortex (Ginsburg, 1986), the quality of this work depends heavily on how the light containing the visual information is refracted onto the retina. As one of the most important processes of light refraction, accommodation of the eye is of great interest to many vision researchers (e.g., Donders, 1864, Duane, 1912, Hamasaki, et al., 1956, Hofstetter, 1965, Johnson, 1976, Charman, 1989, Ramsdale and Charman, 1989, Koretz, et al., 1989, Wolffsohn, et al., 2001, 2002) and is the focus of the current study.

2.2.1 The accommodation process

The change in fixation from an object at one distance to that at another is associated with a related change in the optical characteristics of the eye. The specific change that occurs is a shift of the location of that point in space which is optically conjugated to the retina. It is this process that we define as a change in accommodation. And the difference between the location of the nearest point and that of the farthest point the eye can focus on is termed as the amplitude of accommodation.

To fully understand the mechanism of accommodation, a brief description of the physiological and optical changes involved in the accommodation process is presented. Starting with the emmetropic eye (the far point is infinity) (Figure 4A), assuming the minimum refractive power, parallel light rays from an infinitely far target point are passed through the media of the eye, and refracted to focus on the retina. In Figure 4B, the rays are divergent due to the target moving closer to the eye. At this time, the rays from the target point focus on a virtual position behind the retina due to the unchanging of the refractive power of the eye, consequently, the image is blurred. As the eye's refractive power increases, the retinal focus is acquired (Figure 4C). This process by virtue of which the eye changes its refractive power is termed as accommodation.

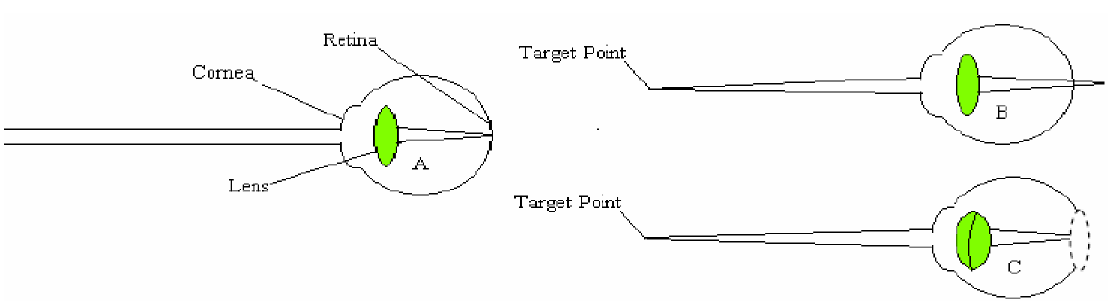


Figure 4: The process of accommodation

During the accommodation process, physiological change, refractive power change, and the change in conjugate distance are usually involved.

- Physiological change: The bulk of the eye's physiological change during accommodation involves the lens. As the eye's refractive power increases, the anterior pole of the lens moves forward, and the posterior lens surface increases its curvature. The lens diameter decreases, the lens capsule tension changes, and the lens sinks slightly toward the pull of gravity. Additionally, the pupil constricts, the anterior chamber becomes shallower, and the retina shifts forward. These adjustments are induced by autonomically innervated changes in the ciliary muscles and the Zonular fibers (Gawron, 1983, Toates, 1972).

- Refractive power change: Physiological change is accompanied by another type of change – the alteration of the eye's refractive power. The total refractive power of a young healthy human eye is found to be approximately 60 Diopters (Diopter = 1/meter, Davey, 1972), which includes the refractive power of the cornea (two-thirds of the total power) and the refractive power of the lens (one-third of the total power). During accommodation, the change of the lens leads to the refractive power change of the eye by up to 10 Diopters (Davey, 1972).

- Change in conjugate distance: Since the refractive characteristics of the eye are difficult to assess directly, the amount of accommodation is usually measured as the reciprocal of the conjugate distance. Assuming the distance (in meters) between the eye and the position of a target point that is focused on the retina is obtained, the amount of accommodation in Diopter (i.e., 1/meter) can be expressed. In applied vision research, including the current study, the physiological and refractive power changes of the eye are generally inferred from the changes in conjugate distance. As for the total refractive power (i.e., 60 Diopters), however, it is based on the actual distance light is refracted on the retina after entering the cornea.

2.2.2 Modeling accommodation

By considering the physiological change, the refractive power change, and the change in conjugate distance during accommodation, many mathematical models have been published to describe and predict the accommodation process, which are usually based on the observation of the actual structural changes of the lens involved in accommodation (e.g., Warren, 1980, Koretz and Handelman, 1982, 1983). For example, in the study conducted by Warren (1980), the accommodation of the eye was modeled via the gradient-index lens model which assumed that the lens of the eye had several gradients and each of the gradients had a unique refractive index to refract light (see Warren, 1980 for mathematical details). Based on the model, the change of the lens during accommodation was modeled to predict the forces provided by the surrounding muscles involved in accommodation. In some other studies such as Koretz and Handelman's (1982, 1983), the accommodation process was modeled based on the observed geometrical changes of the lens with the simplified assumptions about the lens curvature, the internal organization of the lens, and the lens elasticity (see Koretz and Handelman, 1982, 1983 for mathematical details).

Although the predictions of these mathematical models are in agreement with the observed changes of the lens structure (Warren, 1980, Koretz and Handelman, 1982, 1983), they are focused mainly on the static aspects of accommodation (e.g., the amplitude of accommodation) and the prediction of the forces produced by the surrounding muscles to change the lens structure. While it is important to understand the physiological changes of the lens during accommodation, none of the studies is directed to describe another critical part of accommodation, that is, the dynamic aspects such as the temporal duration and speed of accommodation. The reason for this lack is probably due to the late discovery of a reliable way to measure accommodation dynamically (Wolffsohn, et al., 2001). As a result, researchers in the past had to rely solely on mathematical and anatomical techniques to study accommodation. As accommodation per se is a continuous and dynamic process, however, the nature of accommodation cannot be fully explored unless sufficient effort has been dedicated to studying the dynamic aspects of accommodation. Hence, the author hopes that the current study can help fill this void by studying the accommodation process via real-time/dynamic measurement.

2.2.3 The techniques to measure real-time accommodation

The definition of accommodation, again, is the ability of the eye to automatically change the focus of its lens from the seeing at one distance to that at another. In other words, accommodation is a continuous process occurring in a certain period of time. Previous studies have successfully addressed the change of the lens structure during the accommodation process (see Warren, 1980, Koretz and Handelman, 1982, 1983). However, their work fails to answer such questions as: 1) how long does it take the eye to alternate the focus, 2) when does the optical power of the eye start to change, 3) how fast is the change of the focus, and 4) what factors may affect the temporal accommodative characteristics? To answer these questions, the accommodation process has to be recorded dynamically and monitored from the beginning to the end, which can be acquired with the help of autorefractors (Mallen et al., 2001, Chat and Edwards, 2001, Wolffsohn, et al., 2001).

An autorefractor is an infrared triggered open view computerized instrument designed to measure the refractive errors of an eye. As the accommodation process is, in essence, the change of the curvature and shape of the lens so as to create a certain refractive power of the eye to bring image in focus, the measure of the change of the refractive errors of the eye during accommodation can be used to imply the accommodation process (Pugh and Winn, 1988, Wolffsohn, et al., 2001) and thus offers a potential way to study accommodation dynamically. The advantages of the autorefractor, compared with other instruments for refractive prescription (e.g., the Snellen chart and the retinoscope), are that 1) though it measures one eye at a time, the use of an occulator to cover the untested eye allows the subject to view through a semi-silvered mirror binocularly, which creates a normal viewing condition for him or her, and 2) the infrared signal used for the measurement is of a wavelength of 800-900 nm, which is reported not to interfere with one's visual performance, including accommodation (Mallen et al., 2001). As such, the autorefractor is suggested to be capable of measuring the refractive errors of the eye objectively and free of distortion, both of which are of a great value to the objective measure of one's accommodation (Pugh and Winn, 1988, Rucker and Kruger, 2004, Wolffsohn, et al., 2001, 2002).

Nevertheless, the autorefractors available on the market so far (e.g., Shin-Nippon®, Canon®, Nidek®, Humphrey®, and PowerRef®) can only take static refractive measures if the machines are not modified. For example, the Shin-Nippon SRW-5000 autorefractor can take measurement by clicking a joystick on the machine. If the joystick is pressed repeatedly, the machine can continuously take measures at a shortest time interval of about 0.5s, which is suggested to be insufficient to study the dynamic aspects of accommodation (Pugh and Winn, 1988, Wolffsohn, et al., 2002). In order to improve the recording speed, the currently available autorefractors must be modified. The first modification was made on the Canon R1 autorefractor by Pugh and Winn in 1988. By means of altering the signal swept mode of operation to a continuous mode, the Canon R1 was able to measure refractive errors continuously at up to 15 Hz (Pugh and Winn, 1988), which is a acceptable speed for recording the accommodation process (Wolffsohn, et al. 2001). Due to the limitations of the machine, however, it is reported that the modified machine needs calibration for each individual, has a limited working dynamic range (2-3 Diopter), needs relatively large pupils (3.9 mm, Winn et al., 1989), requires the use of a bitebar, and only tolerates a small degree of eye movements (Owens, 1991). As a result, the use of the Canon R1 autorefractor is far from a reliable way to record accommodation.

After 10 years since Pugh and Winn published their work, the continuous and reliable measure of refractive errors is finally realized via newly released autorefractors (e.g., the Shin-Nippon SRW 5000 and the PowerRef PlusOptiX). Similar to the mechanism used in the modification of the Canon R1 (i.e., by allowing the measurement signal to be continuously projected), these modified machines are capable of recording accommodation dynamically at 25 to 60 Hz (Wolffsohn, et al., 2001, 2002, Seidemann and Schaeffel, 2002). Also, with the use of these machines, no fine calibration or bitebar is needed for each individual, and a wide dynamic range (> 6.5 Diopter) and high tolerance to eye movement are achieved (Jainta, et al. 2004, Wolffsohn, et al., 2001, 2004). Therefore, it is suggested that these machines are reliable in recording accommodation continuously and dynamically (Wolffsohn, et al., 2002).

2.2.4 Recording a complete accommodation process

Since the new autorefractors (e.g., the Shin-Nippon SRW 5000 or the PowerRef PlusOptiX) were originally designed to measure refractive errors, the measure of accommodation is inferred from the change of the Spherical Equivalent value (SE, in Diopter), which is one of the refractive measures provided by the autorefractors. SE, by definition, is equal to "sphere refractive error (a measure of the curvature of the cornea and the lens) + ½ cylinder refractive error (a measure of the irregularity of the cornea curvature, in other words, astigmatism)". Based on the definition, SE summarizes the refractive errors of the eye. Since the focus of the eye is determined by both the curvature of the cornea and the lens and the irregularity of the cornea, the measure of SE, which contains the information of both the curvature and the irregularity, is suggested to best infer the focal information of the eye (Mallen et al., 2001, Wolffsohn, et al., 2001, 2002). As the curvature and the irregularity of the cornea remain fixed during accommodation, the change of SE is resulted mostly from the structural changes of the lens, which justifies the use of SE to the study of accommodation.

With the help of the autorefractors, some vision researchers have captured a complete process of accommodation (Wolffsohn, et al., 2001). However, as this technique is relatively new, there is a lack of a standard method to describe and parameterize the general patterns of a recorded accommodation process. The commonly used method is visual and manual detection of critical points (Heron, et al., 2002, Mordi and Ciuffreda, 2004, Wolffsohn, et al., 2001, 2002, 2004). That is, the critical points involved in accommodation such as the start and end points of accommodation are selected manually and visually from the recorded data by the researchers on the basis of his or her experience. Although such an approach is easy to use, it prevents the results of one study from being compared with those of others in that different researchers may select different points based on their own understanding of accommodation. Even if similar points are chosen, any small difference between the points may still result in different findings, because accommodation is a fast and short process (usually described in milliseconds) (Heron, et al., 2002, Mordi and Ciuffreda, 2004, Wolffsohn, et al., 2001).

Hence, one of the objectives of the current study was to develop a replicable way to process the recorded data.

2.2.5 Pilot test results

A pilot study was conducted utilizing the modified Shin-Nippon SRW-5000 autorefractor to assess the accommodation process when the participants were required to alternate their focus due to an abrupt change of a target (see Section 3.3 Experiment setup 2 about the modification of the autorefractor and the recording of dynamic accommodation). Then a mathematical procedure via Savitzky-Golay filtering was developed to analyze the data (see Section 3.3.4 Data processing for detailed descriptions of the processing of the data), which suggests that the accommodation process looks like Figure 5. That is, assuming a person has been asked to focus on a certain image, his or her optical power (measured by the Spherical Equivalent value, SE) will remain relatively constant. After a sudden switch to an image at a different location (indicated by “Trigger” in Figure 5), his or her eyes will first remain relatively unchanged in terms of SE and then start to adjust the focus so as to see the new image clearly (indicated by “Onset” in Figure 5 and determined by the local minimum in the velocity curve). In other words, there is a lag between the change of the images and the onset of accommodation. After he or she fully focuses on the new image, the optical power will reach a new relatively constant value (indicated by “Offset” in Figure 5 and determined by the local minimum in the velocity curve).

Based on this pattern, the accommodation process can be characterized by six parameters: 1) the magnitude of accommodation (MOA, Figure 5), 2) reaction time (RAT, Figure 5), 3) the response time (RPT, Figure 5), 4) the time to accommodate (TTA, Figure 5), 5) the peak velocity (PV, Figure 5), and 6) the percentage of time to reach the peak velocity (Time%, Figure 5). MOA is defined as the difference of the average Spherical Equivalent values between the two steady focus levels before and after accommodation. RAT is defined as the time interval between the known instant of stimulus change and the time at which the response just starts to change from the initial steady state level, and RPT is defined as that between the latter time and that when the response just reaches its new steady state level. As for TTA, it is simply the addition of RAT and RPT (i.e., the total temporal duration of the accommodation process). From the velocity curve, PV is defined as the maximum velocity of accommodation during the response time (RPT), and Time% is the percentage of the response time (RPT) for the velocity to reach its maximum, that is, 100 * the division of the time duration between "Onset" and "Peak Velocity" and the response time (RPT).

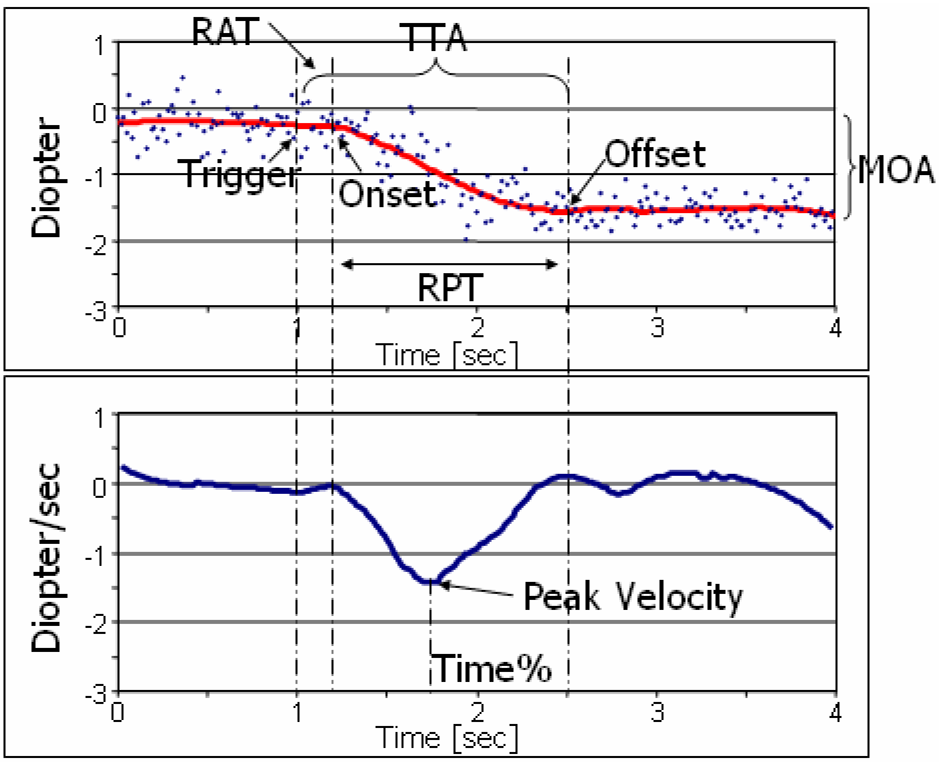


Figure 5: Sample accommodation process and its velocity curve

The choice of these parameters was partially based on the literature and partially based on the focus of the study. Although the magnitude of accommodation (MOA) and reaction time (RAT) have been observed previously (Sun, et al., 1988, Ciuffreda, et al., 2000, and Heron, et al., 2002), the response time (RPT), the total time to accommodate (TTA), the peak velocity (PV), and the percentage of time to reach its peak (Time%)

were created to further describe the dynamic aspects of accommodation (i.e., timing and speed). Compared with the visual detection of the onset and offset of accommodation (Heron, et al., 2002, Mordi and Ciuffreda, 2004, Wolffsohn, et al., 2001, 2002, 2004), the use of the minimum velocities before and after the peak velocity appeared to be more reasonable and reliable for determining the onset and offset of accommodation. Hence, by means of the six parameters, it was expected that most of the dynamic accommodative characteristics of the eye involved in the accommodation process triggered by an abrupt stimulus change could be represented, and thus they were used in the present study to assess the accommodative characteristics of the eye for different age groups, light intensity, and light chromaticity, all of which were expected to play a significant role in one's accommodative ability.

2.3 The effects of aging on accommodation

There are many factors affecting one's accommodation, among which the age-related changes of the eye are the key factor.

2.3.1 The age-related accommodation loss

The history of studying the effects of aging on accommodation dates back over 150 years (Mordi and Ciuffreda, 1998). Numerous studies have clearly and consistently demonstrated a progressive decline in the amplitude of accommodation with the advancing of age (Donders, 1864, Duane, 1912, Hamasaki, et al., 1956, Hofstetter, 1965, Charman, 1989, Ramsdale and Charman, 1989, and Koretz, et al., 1989). This age-related decline starts in childhood (Eames, 1961, Wold, 1967), and extends to middle and older ages (Donders, 1864, Duane, 1912, Turner, 1958, Bruckner, et al., 1987, and Koretz, et al., 1989). The decrease of the accommodative ability makes it more difficult for a person to focus on near objects, leading to presbyopia (the inability of the eye to change its focus from far to near objects caused by aging). In general, this decline becomes problematic at the age of 40-50; at that time the nearest point a middle-aged person can focus on retrogresses to about 1 meter away from the eyes, compared with younger counterparts who can focus on objects as close as 20 cm away from the eyes (Mordi and Ciuffreda, 1998).

Considerable efforts have been made to discover the mechanism of the age-related loss of the amplitude of accommodation (Glasser and Campbell, 1998, Mordi and Ciuffreda, 1998, 2004, Weale, 2003, Strenk, et al., 2005). Generally speaking, it is ascribed to the loss of the elasticity of the crystalline lens and the weakening of the muscles around it. When the eye ages, the lens hardens (Gullstrand, 1909), the activity of the ciliary muscles decreases (Duane, 1922), and the tension of the Zonular fibers declines (Weale, 1962). All of these changes, along with the controversial neural contributions (Elliott, et al., 1990), are considered to impair the lens curvature and cause the age-related accommodation loss, especially its amplitude.

2.3.2 Dynamic aspects of the age-related accommodation loss

Sufficient research has investigated the steady-state accommodation as related to age, including the amplitude of accommodation (Ramsdale and Charman, 1989, Koretz, et al., 1989, Glasser and Campbell, 1998, Mordi and Ciuffreda, 1998), tonic accommodation (Campbell and Primrose, 1953), depth of focus (Campbell, 1957), etc. Due to the lack of studies on dynamic accommodation, the dynamic aspects of the age-related accommodation loss are not fully documented (Ciuffreda and Kenyon, 1983, Ciuffreda, 1991, 1998). Although a recent study conducted by Mordi and Ciuffreda (2004) covered some of the dynamic aspects of accommodation and presbyopia (e.g., the microfluctuations of the accommodation response), their investigation focused mainly on the biomechanical aspects of the lens instead of the dynamic characteristics involved in accommodation (e.g., MOA, RAT, RPT, TTA, PV, and Time% in Figure 5). In terms of these dynamic characteristics, however, only a little work has been done (Sun, et al., 1988, Ciuffreda, et al., 2000, Heron, et al., 2002), which suggests that dynamic accommodation is affected by the age-related changes of the eye.

Specifically, since the age-related accommodation loss reduces the amplitude of accommodation (Mordi and Ciuffreda, 1998), older people may have a much smaller magnitude of accommodation (MOA in Figure 5) compared with younger counterparts, provided that the accommodation triggered by the stimulus change is beyond the remaining accommodative ability of the elderly. Additionally, the dynamic characteristics such as reaction time and the response time (RAT, RPT in Figure 5, respectively) may also be affected by aging (Sun, et al., 1988, Ciuffreda, et al., 2000, Heron, et al., 2002). The reason for that is due to the weakening of the muscles surrounding the lens. Since the muscles are losing their power to contract (Duane, 1922, Weale, 1962), it is likely that a person may spend more time to accommodate when he or she gets older. However, the mixed findings provided by the researchers fail to clearly support this statement. That is, Sun, et al. (1988) failed to find any evidence for an increase in reaction time and the response time with age for continuous stimulus change, while Ciuffreda, et al. (2000) found a slight increase of reaction time at a rate of about 2.5 ms per year under similar test conditions but such was not the case for the response time. The reasons for the mixed findings may be due to: 1) improper instrument, and 2) the manual detection of the onset/offset of accommodation. As the measure of accommodation poses a high demand on the capability of the equipment, some of the autorefractors have shown their limitations on measuring accommodation, one of which is the Canon R1 autorefractor, the most frequently used autorefractor in accommodation research conducted around the year of 2000. Because of its vulnerability to eye and head movement and small pupils (Wolffsohn, et al, 2001), the use of the machine, which is no longer available on the market, may not accurately capture the accommodation process. On the other hand, most of the literature on accommodation so far uses visual detection to manually select the onset/offset point of accommodation (Sun, et al., 1988, Ciuffreda, et al., 2000, Heron, et al., 2002, Mordi and Ciuffreda, 2004), which may result in the failure to correctly determine the critical points of accommodation and also restrict the comparability among studies. Hence, the dynamic accommodative characteristics caused by the age-related changes of the eye still remain unclear in the literature, and to help provide a better understanding of this issue, the present study used a more reliable instrument (the Shin-Nippon SRW 5000 autorefractor, Wolffsohn, et al, 2001) to record accommodation and a replicable mathematical model for data processing to investigate the temporal and spatial features of the age-related accommodation loss. Also, the present study was expected to better elucidate the aging effects on the time to accommodate by breaking it down into five parameters (i.e., RAT, RPT, TTA, PV, and Time%, Figure 5).

2.4 The effects of light on accommodation

Since aging and the age-related physiological changes of the eye both occur within a person, aging can be viewed as an intrinsic factor causing the change of accommodation. As for the extrinsic factors, one of the most important factors is the light reaching the eye, as it is the light that transmits external stimuli which trigger the accommodation process (Hung, et al., 2002). The two fundamental characteristics of the light to be considered in this study are its intensity and chromaticity, which are determined by the energy and wavelength distribution of the light, respectively.

2.4.1 The effects of light intensity

The standard view of accommodation control is that luminance contrast[5] provides the stimulus (Bobier, et al., 1992, Charman and Tucker, 1978, Heath, 1956, Phillips and Stark, 1977). When the luminance contrast of the retinal image changes, or, in other words, the eye defocuses on the image, the information of the defocus is transmitted via the retinal cells to the visual cortex, and then the optical system of the eye starts searching for the point of maximal luminance contrast, leading to the process of accommodation (Rucker and Kruger, 2004). In terms of the retinal cells (i.e., cones and rods), it is reported that only cones are responsible for the detection of the change of the luminance contrast of the retinal image (Kroger and Binder, 2000, Rucker and Kruger,

[5] Contrast luminance: a ratio describing the luminance difference between the object of interest and its background, e.g. Michelson Contrast = (Lmax-Lmin) / (Lmax+Lmin), where Lmax and Lmin are the maximum and minimum luminance of the area, respectively.

2004, Kruger, et al., 2005). As a result, the functionality of cones is expected to affect the sensitivity of the detection of the defocus and therefore play a critical role in the accommodation process.

Specifically, cones are one of the two kinds of photoreceptors on the retina (the other is rods). They are dominant in the foveal area of the retina, and are responsible for color vision and the perception of fine details and repaid changes of the details. In order to perceive color, there are three types of cone photopigments on the retina specialized to absorb portions of light over a limited range of wavelengths, and each has peak absorption at a particular region of the spectrum (Schiffman, 2005). Because of their peak sensitivities to short, medium, and long wavelengths, these three cone photopigments are referred to as S-cones, M-cones, and L-cones, respectively.

Sufficient studies have demonstrated that cones function only under relatively bright light, and their activity declines rapidly with the decrease of the intensity of light reaching them (Roorda and Williams, 1999, Schiffman, 2005). Usually, cones function under the luminance level of up to 10^6 cd/m^2 (the extreme condition) and continuously reduce their sensitivity until the luminance level decreases to 1 cd/m^2, below which little functionality remains in cones (Kandel, et al., 2000).

Because of this relationship, the intensity of light has been demonstrated over decades to affect the accommodation process (Johnson, 1976, Rosenfield, 1993, Arumi et al., 1997, Jackson, et al., 1999). In the study conducted by Johnson (1976), the decrease of the stimulus luminance altered clearly the accommodative performance. Johnson (1976) investigated that the accommodation responses at each stimulus distance, in terms of the actual focal point, differed under four certain luminance levels. Under the highest luminance level, the four response curves found from four participants were all similar to the optimal curve. The deviations from the optimal values increased under declined luminance levels, especially for those responses to the stimuli at distances away from a certain intermediate value. Moreover, at the lowest luminance level, the accommodation responses seemed to be the same across the stimulus distances, suggesting that the accommodation response of the eye remained at a certain focal distance in extreme darkness. This phenomenon is called "dark focus" or "tonic accommodation", which supports that the sensitivity of cones determines one's accommodation (Rucker and

Kruger, 2006). In other words, since cones stop functioning in darkness, the eye is unable to accommodate so that its focal point remains unchanged.

In spite of the knowledge with regard to the effects of light intensity on the static aspect of accommodation (e.g., the location of the focal point after one accommodates), little is known for its effects on the dynamic accommodative characteristics. However, it is expected that the observed decrease of the accommodation response under low intensity of light may be accompanied by the change of the dynamic characteristics. Specifically, as cones reduce functionality in darker conditions, the eye may become less sensitive to the stimulus for accommodation. As a result, it may take more time for the eye to start accommodating (measured by reaction time, RAT in Figure 5), while, on the contrary, the accommodation time (measured by the response time, RPT in Figure 5) may decrease due to the lower amplitude of accommodation found in reduced luminance conditions (Johnson, 1976). In this sense, it is necessary to study the effects of light intensity on dynamic accommodative characteristics, which can help us better understand the accommodative performance of the eye at nighttime conditions.

2.4.2 The effects of light chromaticity

The chromaticity of light is the quality of the color of light as determined by its dominant wavelength and the prevalence of other non-dominant wavelengths. Since cones are responsible for detecting the stimulus for accommodation and different cones are sensitive to light of different wavelengths, it is reasonable to assume that the chromaticity of light also influences the accommodation process. In fact, less accommodation has been found when human subjects read in blue light than that when they read in red light (Kroger and Binder, 2000). Specifically, in Kroger and Binder's (2000) study, young adults were recruited to perform a task similar to reading and writing under various conditions of the chromaticity of light. Compared with the accommodation when performing the task in white light, the amplitude of accommodation was increased in red light and decreased in blue light by up to 0.5 Diopters (Kroger and Binder, 2000), which indicates a change of accommodation in light of different chromaticities.

Consistent with their results, Seidemann and Schaeffel (2002) also found accommodation shift under different quasi-monochromatic illumination conditions. In their experiment, each participant was asked to read a text at 3-Diopter distance, which was illuminated by a beam passing through different interference filters. Each light condition had a peak wavelength ranging from 480 nm to 655 nm. The results indicated that in the light of shorter wavelength (i.e., bluish) the participants were unable to fully accommodate at the target. Although no statistically significant difference in accommodation shift was found among 480 to 555 nm of light and among 590 to 655 nm of light, significant difference did occur between 480 nm and 655 nm of light (Seidemann and Schaeffel, 2002), suggesting that though there was a decline of the magnitude of accommodation associated with the decrease of light wavelength, only lights having distinctively different wavelengths and chromaticities (e.g., blue vs. red) might lead to a remarkable change of accommodation. In this sense, light of distinctive chromaticities (e.g., blue vs. red) was chosen in the current study to address the effects of light chromaticity on the accommodation process.

In addition to the two studies, many researchers have found the effects of light chromaticity on the amplitude of accommodation (e.g., Wilson, et al., 2002, Rucker and Kruger 2004, Kruger, et al., 2005). Most of them suggest that the cause of the chromaticity effects is ascribed to the longitudinal chromatic aberration (LCA) and the functionality of cones (Fincham, 1951, Wilson, et al., 2002, Rucker and Kruger, 2004, Kruger, et al., 2005).

LCA is the chromatic dispersion of light by the ocular media due to the different refractive indices for different wavelengths of light (Figure 6). Recall that accommodation happens when the luminance contrast of the retinal image changes, or in other words the eye defocuses on the image. The explanation of the chromaticity effects by LCA is that due to the difference in refractive index for different wavelengths of light, the information of defocus will be transmitted differently onto the retina and result in the difference in accommodation. If this is correct, studying accommodation by different monochromatic lights will be an optimal way to show the chromaticity effects. However, studies suggest that only some of the subjects were able to accommodate in monochromatic light and showed the chromaticity effects (Fincham, 1951, Wilson, et al., 2002), indicating that the difference in refractive index is not the sole cause of the chromaticity effects.

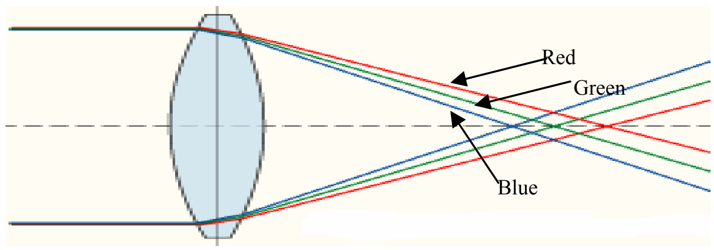


Figure 6: Longitudinal chromatic aberration

Along with LCA, a complementary explanation is that the three kinds of cones also contribute to the chromaticity effects (Rucker and Kruger, 2004, Kruger, et al., 2005). Since the S-, M-, and L-cones are sensitive to short, intermediate, and long wavelength of light respectively, it is suggested that different cones are activated by different wavelengths of light in the process of accommodation (Crane, 1966). As a result, the difference in the performance of the three cones may lead to the chromaticity effects on accommodation. For example, two successive studies on dynamic accommodation conducted by Rucker and Kruger (2004) and Kruger, et al. (2005) have demonstrated that L- and M-cones contribute more than S-cones to luminance and chromatic signals that produce accommodation response, which supports the less accommodation found when human subjects read in blue light (shot wavelength) than that when they read in red light (long wavelength) (Kroger and Binder, 2000). Moreover, since the sensitivity of S-, M-, and L-cones differs between different subjects (Kruger, et al., 2005), the contributions of cones also help explain why some subjects can accommodate in monochromatic light while others cannot. As such, the chromaticity effects may be a combination of LCA and cone functionality (Kruger, et al., 2005).

To conclude, although vision researchers are still debating on the mechanism of the chromaticity effects on accommodation, it is clear that the chromaticity of light plays a vital role in the accommodation process, which has been supported by numerous studies directed for investigating the chromaticity effects on the amplitude of accommodation

(Fincham, 1951, Wilson, et al., 2002, Rucker and Kruger, 2004, Kruger, et al., 2005). As for its effects on the dynamic accommodative characteristics, it is expected that light of different chromaticities should result in the change of the dynamic characteristics, as light of different chromaticities creates different stimuli for the eye to accommodate. Since there is no study verifying this possibility, the dynamic characteristics assessed in the present study can help elucidate it and expand the knowledge of the chromaticity effects on accommodation.

2.4.3 Relationship between the intensity and chromaticity of light and aging

As discussed earlier, the advancing of age results in the physiological changes of the crystalline lens and the muscles around it. A study conducted by Curcio, et al. (1996) suggests that aging also has an adverse effect on the photoreceptors on the retina. When one gets older, the photoreceptors start to degenerate and lose their functionality. It starts with loss of rods and then cones. With the degeneration of cones, the stimulus for accommodation, which is carried by light, may not be efficiently transmitted to the brain. As a result, the effects of light on accommodation may interfere with the effects of aging. In other words, the age-related changes of the lens and the muscles may have a different impact on the accommodation process, if the accommodation is triggered by light of different intensities or chromaticities. For example, due to the accelerating loss of cones at older ages (Curcio, et al., 1996), older adults, compared with younger and middle-aged counterparts, may exhibit a more remarkable decline of the dynamic accommodative performance when the ambient conditions are changed from daytime to nighttime. Additionally, as the three kinds of cones (i.e., S-, M-, and L-cones) recede in a different pace with aging (Haegerstrom-Portnoy, 1988, Werner, et al., 2000), the effects of light chromaticity may interact with the effects of aging as well. Hence, with the inclusion of both the age-related changes of the lens and the muscles and the intensity and chromaticity of light, the age-related accommodation loss is expected to be better elucidated by the present study.

In summary, this review covered the physiological characteristics of the eye, the basics of accommodation, the measure of accommodation, and the effects of aging and light on accommodation. Based on the review, a study was conducted to investigate the general patterns of the accommodation process, especially the temporal features, via the modified Shin-Nippon SRW-5000 autorefractor across different age groups, light intensity levels, and light chromaticities.

3. METHODS

3.1 Participants

In total, thirty participants were recruited for the study, ten from each of the three age groups, that is, younger group (20 to 29 years old, mean = 24.1, s.d. = 3.22), middle-aged group (40 to 49 years old, mean = 45.4, s.d. = 3.13), and older group (60 to 69 years old, mean = 64.9, s.d. = 2.91). Informed consent was approved by the Institutional Review Board (IRB) of Virginia Tech and was signed by each of the participants. All of the participants were free from any eye disease (especially, color blindness) 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 Bausch & Lomb ® Vision Tester) and static contrast sensitivity test (via Vistech ® Contrast Sensitivity Chart) were conducted as screening tests to ensure that each participant met the criteria.

The sample size required for the experiment was estimated from the results of the pilot study, which, as mentioned earlier, was conducted to assess the capability of the autorefractor to accurately measure the accommodation process. The inter-subject variability of the magnitude of accommodation (MOA) among three age groups was used to calculate the power for the study. The use of MOA for the power analysis, instead of the other parameters (e.g., reaction time and the response time), was because: 1) the effects of aging on the magnitude of accommodation had been well documented, 2) the results of this parameter in the pilot study aligned well with published values (Hamasaki, et al., 1956, Glasser and Campbell, 1998, Mordi and Ciuffreda, 1998, 2004), and 3) based on the literature review, it was expected that the change of the magnitude of accommodation was accompanied by the change of the temporal characteristics (e.g., reaction time and the response time). Hence, the power of the test was determined by focusing on sample sizes large enough to detect differences in the magnitude of accommodation among younger, middle-aged, and older individuals with high probability (>0.70).

The formula for calculating the power is provided below (O'Brien and Lohr, 1984):

$$\text{Power} = \text{Prob}(F>F_{crit}, \nu_1, \nu_2, NC) \qquad \text{(Equation 1)}$$

where ν_1 = r-1, ν_2 = r(n-1), and r, n are the number of groups and the number per group, respectively. In the formula, NC is the noncentrality parameter, which is an indicator of the true difference of the variable of interest, and is determined by Δ, the difference of the variable between two consecutive groups, σ^2, the mean squared error, and n.

As such, to calculate the sample size n, we must know the values of r, Δ, and σ^2. Since there were a total of 3 age groups, r was equal to 3. As for Δ and σ^2, the estimation was based on the pilot study, which suggested that Δ was approximately 0.6, and σ^2 was approximately 0.16. Thus, 10 participants in each group should be sufficient to detect the specified differences (the estimated effect size based on Δ and σ^2 was 1.605) with risks of Type I error of 0.05 and Type II error of < 0.20 (Power > 0.80) (Table 1). Therefore, there were a total of 30 participants recruited for the study.

In fact, based on the results of the study, a post hoc power analysis indicated that using a sample size of 10, the actual power for detecting the age-related changes of the magnitude of accommodation was greater than 0.90.

Table 1: Sample size and power

Sample size per group (n)	NC	Power
7	7.56	0.61
8	8.64	0.69
9	9.72	0.75
10	**10.80**	**0.81**
11	11.88	0.84
12	12.96	0.88
13	14.04	0.91

3.2 Experiment setup 1 – The stimulus

To study the accommodation process, vision researchers usually use a Maltese cross (Figure 7) or a sine- or square-wave grating as target to facilitate the fixation of the eyes, and move the target by means of movable tracks (Jainta, et al., 2004, Heron, et al., 2002, Rucker and Kruger, 2004), optical mirrors (Johnson, 1976, Mordi and Ciuffreda, 2004) or computer programs (Wolffsohn, et al., 2001, 2004) to trigger accommodation. In the current study, the accommodation process ascertained was a complete process associated with accommodation when one alternated the focus from a far target to a near target. For this purpose, a mirror machine (Figure 8) was used to create an instant of target change by flipping down a mirror controlled by the experimenter. A fixation board (Figure 9), which came along with the Shin-Nippon SRW-5000 autorefractor, was placed at 4 m away from the subject's eyes which acted as a constant far target with the diopter value of 0.25 Diopters. As for the near target, a Maltese cross was placed at an adjustable distance (Condition 1) or a fixed distance (i.e., 70 cm, Condition 2) away from the subject's eyes which acted as the near target with the diopter value of about 1.45 Diopters for Condition 2. The choice of 4 m and 0.7 m was partially based on the normal range of the focal point of the eyes when a driver was looking forward or reading the dashboard while driving (Atsumi, et al., 2004).

Due to the age-related decline of the amplitude of accommodation, the stimulus for accommodation was presented in two ways, namely Condition 1 and 2. Under Condition 1, the age-relation recession of the nearest point the eye can focus on was used to determine the location of the near target. That is, during the experiment, a push-up method (Hamasaki, et al., 1956, also see Section 3.5.2 The actual test session) was used to determine the nearest point the participant can focus on. Then the near target was placed at this point. Since the screening test guaranteed that the participant could focus on the far target placed at 4 m, Condition 1 assessed his or her accommodative ability by giving a stimulus he or she could fully accommodate. In case that the participant had the ability to focus on 70 cm or closer, the near target was placed at 70 cm away from the participant, and only Condition 2 was tested.

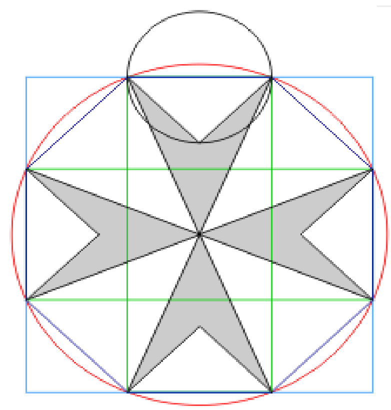


Figure 7: The Maltese cross (the shadow area)

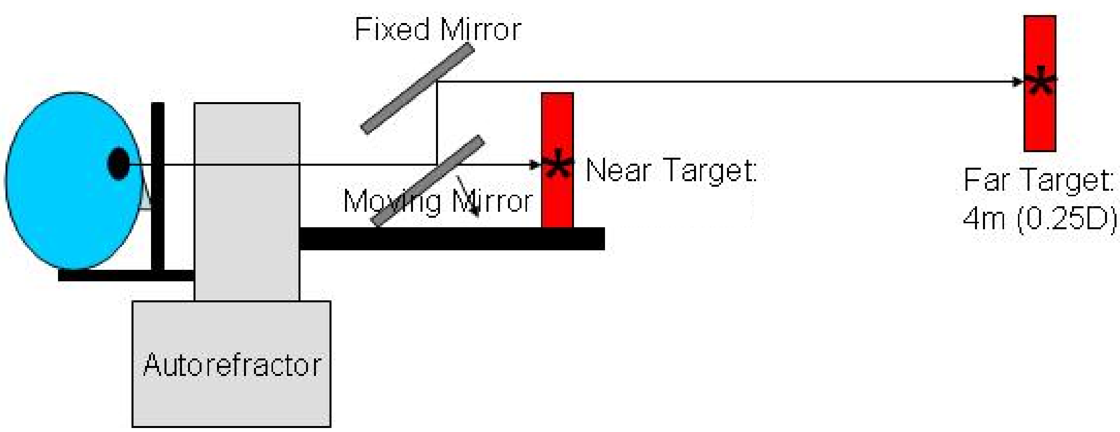


Figure 8: The mirror machine and the autorefractor

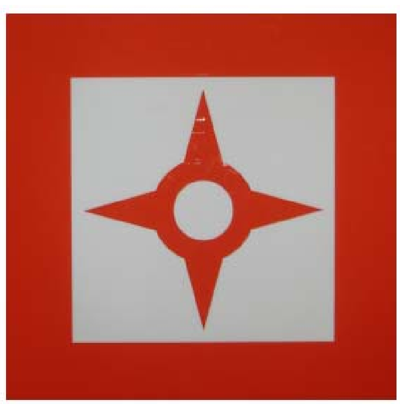


Figure 9: The fixation board

While Condition 1 allowed the participant to fully accommodate the stimulus, different stimuli were actually given to different participants, which might result in the failure to compare the accommodative characteristics among different age groups. As such, under Condition 2, the near target was placed at a fixed distance (i.e., 70 cm away from the eye), which created a constant stimulus change for each participant. By analyzing the results from the two conditions, it was expected that the stimulus for accommodation would not be a confounding factor which might prevent the discovery of the effects of aging and the intensity and chromaticity of light on accommodation.

Additionally, in order to test the effects of light intensity and light chromaticity, the Maltese cross was displayed by a Dell laptop, and the brightness and chromaticity of the cross were adjustable. Based on the normal lighting conditions for dashboard signal display (Lockhart and Raj, 2005), there were two light intensity levels and two light chromaticity levels displayed by the laptop. The two intensity levels were 100 cd/m^2 (daytime) and 20 cd/m^2 (nighttime) (measured by the Minolta CS-100 photometer when the laptop was loaded with a blank white slide), and the two chromaticity levels were blue (RGB value: Red=0, Green=0, Blue=254, chromaticity coordinates[6]: 0.152, 0.130, 11.9 cd/m^2) and red (RGB value: Red=202, Green=0, Blue=0, chromaticity coordinates: 0.524, 0.333, 11.2 cd/m^2).

As such, the experiment was designed 1) to create an instant stimulus change from far to near targets using the mirror machine (Figure 8), and 2) to simulate a situation that a driver must read dashboard information while driving. For this purpose, the far target was placed at 4 m away via a fixation board (Figure 9), while the near target (at the nearest point or at 70 cm away) was a Maltese cross displayed by a laptop at two intensity levels (daytime vs. nighttime) and two chromaticity levels (blue vs. red).

[6] The chromaticity coordinates were measured by a Minolta CS-100 photometer for a 2^0 observer following the CIE 1931 (x, y, Y) criteria.

3.3 Experiment setup 2 – The measure of accommodation

3.3.1 The Shin-Nippon SRW-5000 autorefractor and its mechanism

By using the mirror machine to trigger accommodation, the accommodation process was recorded by the Shin-Nippon SRW-5000 autorefractor (Figure 10), also called the Grand Seiko WV-500 autorefractor. It is an infrared open-view autorefractor, which takes static measure of refractive errors one eye at a time and has been shown to be accurate and valid for measuring refractive errors of the eye in both adults (Mallen et al., 2001) and children (Chat and Edwards, 2001), and has a great potential benefit for accommodation research studies (Mallen et al., 2001).

Figure 10: The Shin-Nippon SRW-5000 autorefractor

The basic mechanism of the autorefractor is described as follows: for each measurement, a ring target of infrared light is projected to the subject and imaged after reflection off the retina. The infrared light is first collimated and passes through rectangular masks housed in a rotating drum. The light then passes through a beam splitter to the optometer system. This system moves laterally via a lens, named as the Badal lens in honor of its inventor, to find the optimal focus of the ring image on the retina based on the refractive conditions of the eye (Figure 11). Optimal focus is achieved when a peak signal is received from the light sensor. The polarized beam splitter then effectively removes reflected light from the cornea whereas the ring image on the retina passes through the polarized beam splitter. Finally, the system analyzes the reflected ring image to derive the refractive prescriptions of the eye.

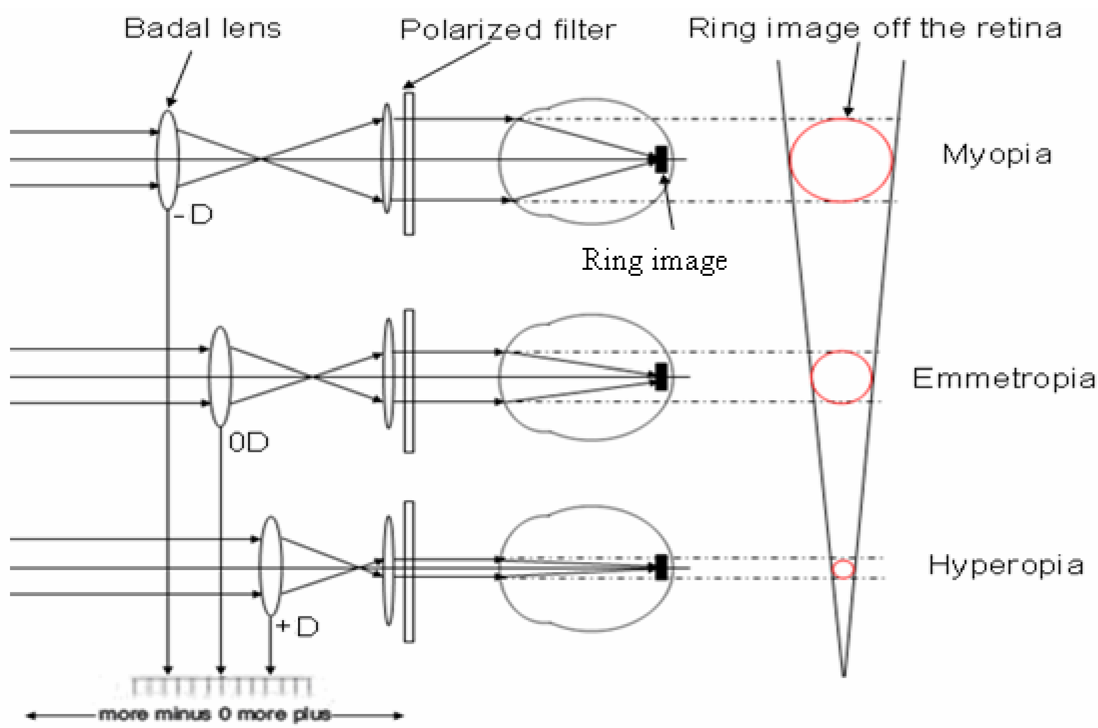


Figure 11: The movement of the Badal lens and the measure of refraction

According to Figure 11, it is clear that the movement of the Badal lens creates the change of the ring image for the eye of different refractive conditions so as to bring the ring image on focus. As such, there is a relationship between the size of the ring image and the refractive conditions of the eye, based on which the autorefractor was designed to provide refractive prescriptions. Figure 12 illustrates this relationship. That is, assuming an emmetropic eye (the bottom graph in Figure 12) 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 Diopters) and zero cylindrical error. At this position, there is a relationship that $\beta_1 = \beta_2$, due to the symmetry of the ring signal. 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. As $L/(1/F) = a/\gamma_0$, $a = L*F*\gamma_0$, which is also the radius value for the ring signal before entering the cornea. Since the emmetropic eye has D_0 total refractive power, the distance between the cornea and the retina should be approximately $1/D_0$.

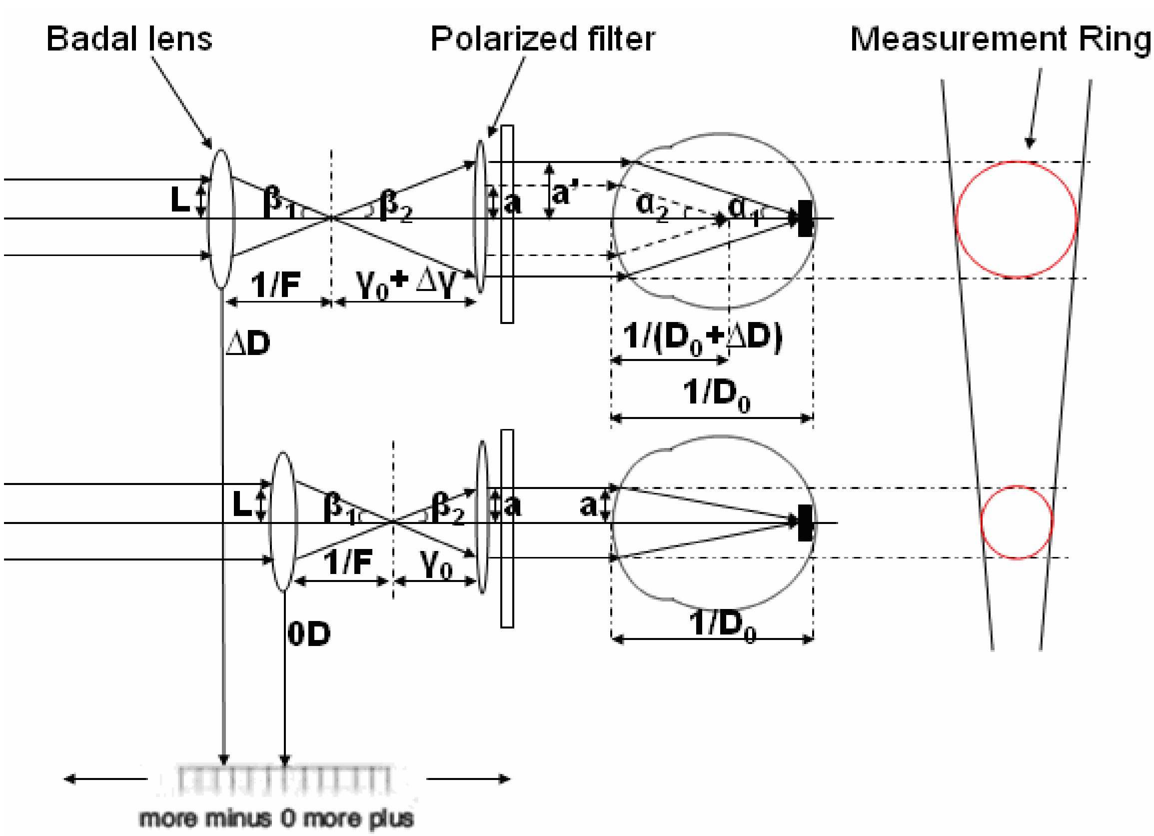


Figure 12: The relationship between the Badal lens and the spherical refractive error

If the emmetropic 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, the upper graph in Figure 12), and the total refractive power of the eye becomes D_0+ΔD. Since the purpose of the Badal lens is to make the measurement ring signal be refracted onto the retina, the lens will move Δγ so as to make the ring signal be focused on the retina, which is 1/ D_0 away from the cornea, instead of a point which is 1/(D_0+ΔD) 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 (<2.9mm) (Mallen, et al., 2001), it is assumed 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* γ_0, a' = L*F*(γ_0+ Δγ).

Thus, $\tan(\alpha_1) = \dfrac{a}{1/(D_0+\Delta D)} = \dfrac{L*F*\gamma_0}{1/(D_0+\Delta D)}$, (Equation 2)

$\tan(\alpha_2) = \dfrac{a'}{1/D_0} = \dfrac{L*F*(\gamma_0+\Delta\gamma)}{1/D_0}$, (Equation 3)

and $\tan(\alpha_1) = \tan(\alpha_2)$. (Equation 4)

Therefore, $\Delta\gamma = \dfrac{\gamma_0}{D_0}\Delta D$ (Equation 5), which indicates that there is a linear relationship between the movement of the Badal lens (Δγ) and the spherical refractive error (ΔD). So long as γ_0 and D_0 for the emmetropic eye are known, the relationship can be quantified.

According to the relationship described above, which is between the movement of the Badal lens and the spherical refractive error of the eye, it is expected that a similar relation exists in the present study between the movement of the Badal lens and the Spherical Equivalent value (SE) of the eye. This is because the cylindrical refractive error is weighed half in SE and the screening test guaranteed that each participant had normal vision with little astigmatism (i.e., no or very small cylindrical error). As such, a fairly straight relationship between the Badal lens and the SE value is expected, based on which a technique using LabVIEW programming was developed by Wolffsohn, et al. (2001) to continuously derive the SE value for accommodation research, and was applied in the current study (see Section 3.3.2 The modification of the autorefractor and Section 3.3.3 Calculation SE via LabVIEW programming).

To summarize, with the movement of the Badal lens, the instrument measures the refractive errors of the eye, which include the spherical refractive error, the cylindrical refractive error and the axis, and a summary value – Spherical Equivalent, SE. As the focus of the eye is determined by the combination of the spherical and cylindrical errors, the purpose of using the autorefractor in this study was to provide a continuous measure of the Spherical Equivalent of the eye, which was accomplished by the modification of the autorefractor and LabVIEW programming.

3.3.2 The modification of the autorefractor

In its normal static mode of operation, when pressing the measurement switch on the joystick of the Shin-Nippon SRW-5000 autorefractor, the measurement ring is illuminated momentarily, and the image of the ring is analyzed. In order to convert the instrument to allow dynamic and continuous recording, the measurement ring has to be permanently illuminated. To achieve this, the "sales mode" menu of the instrument needs to be altered to set the "Ref. Led" from "Auto" to "On", which makes the autorefractor continuously illuminate the measurement ring and collect the reflected ring image (Wolffsohn, et al., 2001).

After achieving a continuous reception of the ring image, the ring image is analyzed externally, as the embedded image analysis system in the autorefractor cannot analyze the image dynamically. In order to obtain the SE value from the ring image, the diameter of the ring image is calculated, and the SE value is predicted because of the linear relationship between the diameter of the ring image and the SE value (Figure 12, and also see Wolffsohn, et al., 2001, 2004).

For this purpose, the signal containing the reflected ring image is linked to a National Instruments (NI) PCI-1407 image acquisition card in a Pentium IV 2.40 GHz PC via the BNC connector on the output panel of the instrument. The extracted image is then analyzed to obtain the diameter of the measurement ring using LabVIEW 8.0 programming and NI Vision Module 8.0.1 software (National Instruments, Texas, USA). To provide a better understanding of how the image is analyzed, the methodology of the programming (Figure 13) is introduced as follows:

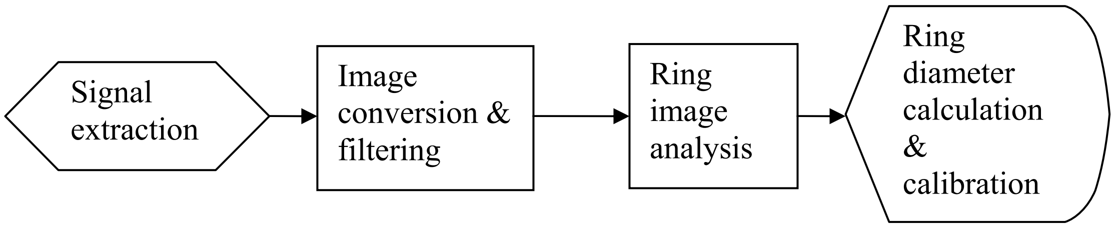


Figure 13: The analysis of the reflected image

3.3.3 Calculation of SE via LabVIEW programming

In general, the program aims to calculate the diameter of the measurement ring. For this purpose, the center of the measurement ring is estimated after the original signal is extracted, converted into binary form, and filtered to leave the bright measurement ring alone. Then the information of the center of the measurement ring is used to plot a horizontal line in the original image passing through the center, and the edges of the measurement ring along the horizontal line are detected and the diameter of the ring is calculated based on the coordinates of the edges. Finally, a calibration procedure is used to convert the diameter value into the actual Spherical Equivalent value for interpretation.

3.3.3.1 Signal extraction

As mentioned earlier, the Shin-Nippon SRW-5000 autorefractor collects the measurement ring image reflected off the retina and calculates the refractive errors based on the reflected image. In order to help the tester capture the ring image correctly, the autorefractor has an internal camera and a video monitor which display the reflected image along with some alignment markers and previous measures (Figure 14). At the same time, the instrument outputs the exact information as an NTSC (National Television Systems Committee) video signal via the BNC port on the output panel.

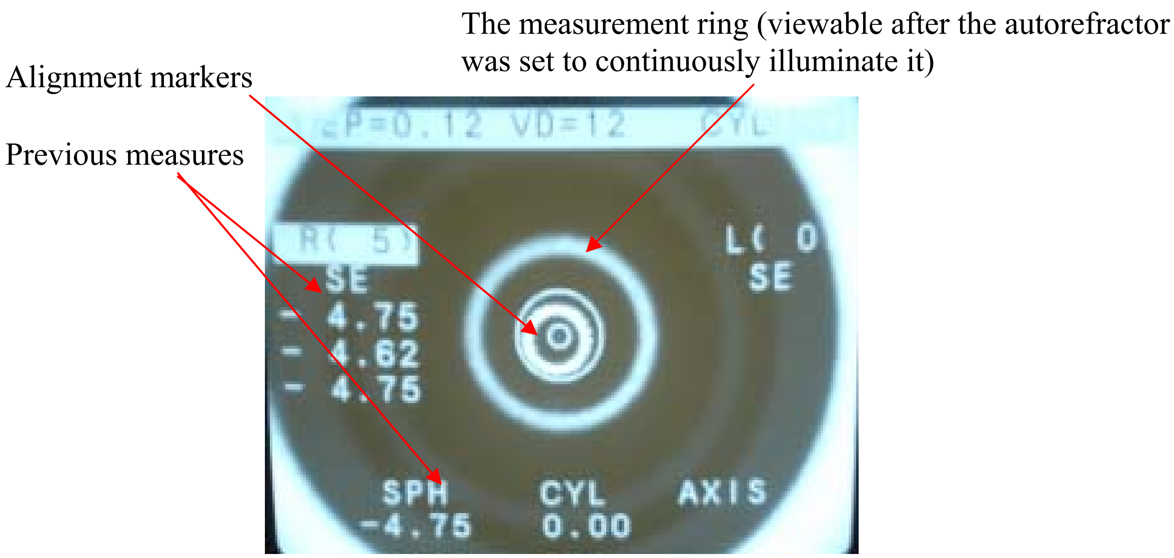


Figure 14: The video image

The NTSC signal is a standard video signal containing the pixel information (256 values: 0~255; 0 means black and 255 means white) for television display at a frame rate of 30 fps (frames per second) and 525 horizontal scan lines, and is widely used in most of the Americas and some parts of East Asia. As the signal is originally for television display, it is extracted for computer processing via the NI PCI-1407 image acquisition card. By means of partial image requisition, only the measurement ring and the alignment markers inside are captured (Figure 15, the left graph). As the NTSC signal consists of two interlaced fields per frame (i.e., 2:1 interlacing), the PCI-1407 card has the ability to extract each field from a frame, which doubles the sampling frequency to 60 Hz by compensating the original image with a half-height image (Figure 15, the right graph). Because the horizontal diameter of the half-height image is the same as that of the original image, the calculation of the ring diameter is still the same with the half-height image.

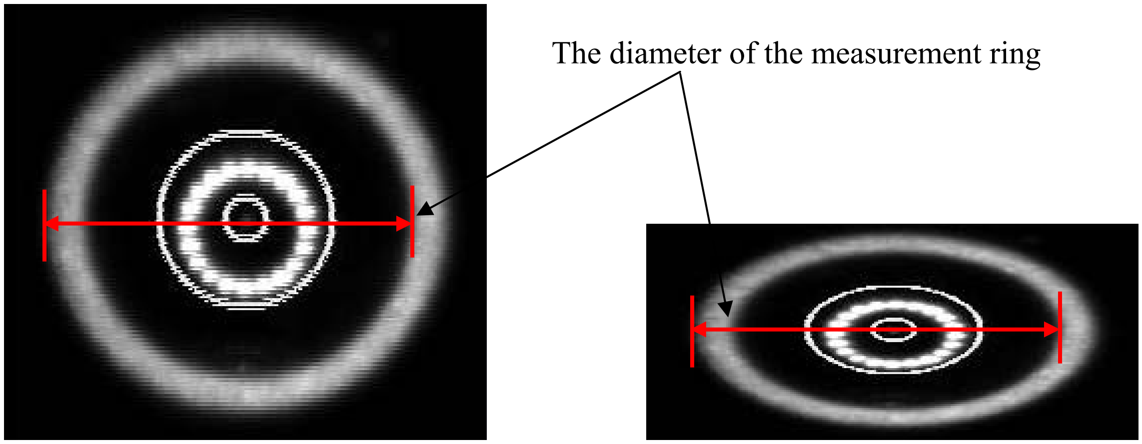


Figure 15: The originally captured image (left) and the half-height image (right)

3.3.3.2 Image conversion and filtering

As the half-height NTSC image contains not only the measurement ring but the alignment markers as well (Figure 15, the right graph), the image is converted into binary form to facilitate image filtering to eliminate the alignment markers. The reason for the conversion is that the half-height image contains pixels of low intensity which are difficult to discern under the unconverted form. That is, these dark areas in the unconverted form (Figure 15, the right graph) still contain pixels of non-zero intensity, which has to be filtered out along with the alignment markers before analyzing the measurement ring image. Hence, in order to better distinguish the dark pixels, the image is converted into binary form by assigning a fixed level of pixel intensity to each pixel within a given pixel intensity threshold range, namely thresholding image analysis (Figure 16). For example, Figure 17 (the left graph) is a binary form of the half-height image by assigning pixel intensity one to all of the pixels having intensity from 1 to 255. The graph indicates that the pixels in most areas have a non-zero value, which blurs the ring image. In order to leave the bright measurement ring alone, the pixels of low intensity must be filtered by assigning them a pixel value of zero via thresholding image analysis.

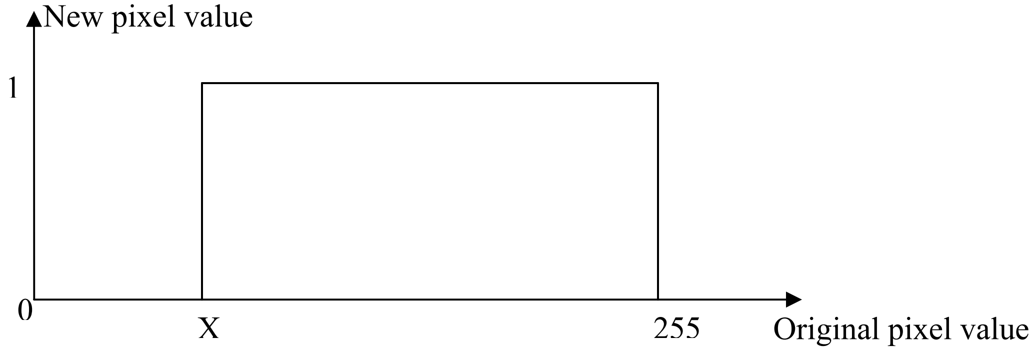


Figure 16: Principle of thresholding image analysis

Figure 17: Binary forms

As shown in Figure 17 (the middle graph), with the increase of the lower threshold ("x" in Figure 16), the binary form of the NTSC signal approaches an image that contains only the bright measurement ring and the alignment markers. As the measurement ring is elliptical and symmetrical, which allows its center to remain unchanged with whatever the width of the ring is, the thresholding analysis can be stopped as long as the measurement ring in the filtered image looks similar to that in the original image (Figure 15, the right graph).

After obtaining a clear image of the measurement ring and the alignment markers, the particle removal algorithm embedded in the NI Vision module is used to remove the alignment markers, which results in a clear measurement ring image (Figure 17, the right graph). The particle removal algorithm, simply speaking, works on the number of particles in a clump. If the number of particles is less than a predefined value, the algorithm removes the entire clump (Equation 6). Since the area of the alignment markers is much smaller than that of the measurement ring, it is expected that the particles in the area of the alignment markers are less than those in the area of the measurement ring, which enables the particle removal algorithm to eliminate the alignment markers and leave the measurement ring alone (Figure 24, the right graph).

$$\text{Particle Value} = \begin{cases} 0, & \text{if} < \text{a predefined value} \\ \text{Unchanged}, & \text{if} >= \text{a predefined value} \end{cases} \quad \text{(Equation 6)}$$

3.3.3.3 Ring image analysis

After obtaining a clear measurement ring image, the center of the measurement ring is estimated via an NI Vision function called “Find Circular Edge”, which searches the edge of the measurement ring and outputs the best-fit circle with the information of the center of the circle (Relf, 2004, and Figure 18, the left graph). Since the measurement ring is elliptical and has the same center as its best-fit circle, the center of the circle is used as the center of the measurement ring to calculate the horizontal diameter of the ring.

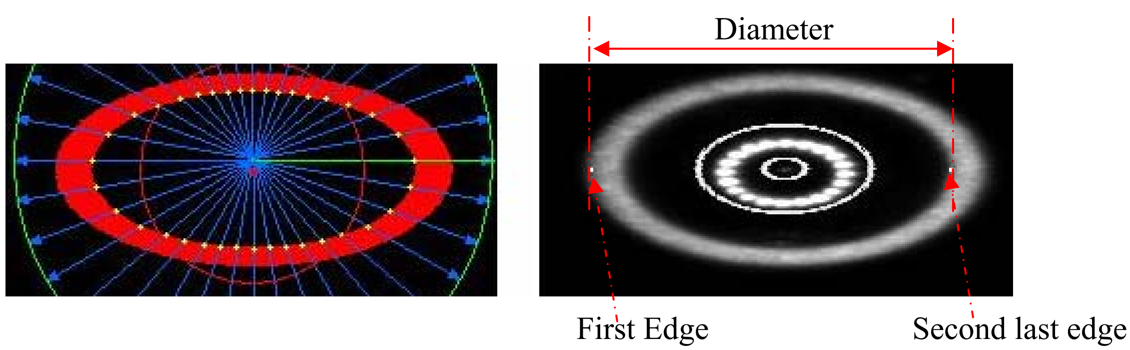


Figure 18: Center and edge detection

Given the center of the measurement ring, the calculation of the diameter of the measurement ring is achieved by detecting the edges of the measurement ring along a horizontal line passing through the center of the ring. In image analysis, an edge is defined as a significant change by a predefined threshold level of the pixel value between adjacent pixels in an image (NI Vision Concepts Manual, pg. 210). Since the binary form of the NTSC image only has binary pixel value (i.e., 0 and 1), the edge detection is performed in the original image (Figure 18, the right graph) so as to maximize the resolution of the edge detection algorithm provided by the LabVIEW Vision module. Specifically, in terms of the resolution of edge detection, conventional image analysis for edge detection is limited to a resolution of one pixel value for a given pixel threshold level. In a real image, however, an "edge" is contained within a pixel "staircase" of changing intensity (i.e., if the values of two successive pixels are 10 and 20, there should be pixel value of 11, 12, 13, etc. existing between them.). By fitting the "staircase" with a quadratic profile (using Labview programming and Vision software), a given pixel threshold level (used to detect the edge of the measurement ring) can be extrapolated to an accuracy of at least 1/1000th of a pixel, allowing a system resolution of 0.0003 Diopters (Wolffsohn, et al., 2001). As a pixel threshold level in NI Vision module must be an integer number (Relf, 2004), the original half-height image has to be used to make the extrapolation algorithm effective in that the binary form is confined within the pixel value between 0 and 1.

As a result, in order to detect the edges of the measurement ring in the non-binary-form image, only the first and second last edges (Figure 18, the right graph) are extracted and used to calculate the diameter of the measurement ring, which eliminates the possibility of using the edges of the alignment markers as the edges of the ring. The reason why the second last edge is chosen instead of the last edge is that the calculation of the diameter based on the outer and inner parts of the ring can minimize the effects of blur of the image on the ring diameter calculation (Wolffsohn, et al., 2001). That is, if the blur of the image occurs (e.g., due to the defocus of the eye), the measurement ring may become less sharp and the size of the ring may be inflated. As the outer part of the ring on one side and the inner part on the other side inflate in the same direction, the change of the distance between them due to the blur is minimal, compared with distances between two outer or inner parts of the ring. As such, the calculation of the diameter of the ring is based on the outer and inner edges of the ring image.

Last but not least, the pixel threshold level used to detect an edge is set at a pixel value of 20 based on a pilot study conducted to assess the capability of the LabVIEW program to measure the accommodation of older people. In other words, the edge of the measurement ring is detected if a change of a pixel value of 20 between adjacent pixels occurs at a certain point of the image. Although it is still reasonable to use some other numbers close to 20 as the threshold level, the calibration procedure described below ensures that any number close to 20 should have the same capability to detect the edges.

3.3.3.4 Ring diameter calculation and calibration

After detecting the edges and achieving the coordinates of the edges, the diameter of the measurement ring is obtained by calculating the distance between the outside edge of one side of the measurement ring and the inside edge of the other side (Figure 18, the right graph), which minimizes changes in measurement ring diameter when the instrument is unfocused (Wolffsohn, et al., 2001).

As the diameter calculated is described in pixel value, it has to be transferred to the Spherical Equivalent (SE) value for interpretation. For this purpose, simultaneous static (by pressing the joystick on the autorefractor) and dynamic (by the program) accommodative measures are made via a model eye (Skia/Retinoscope Trainer, Heine, Germany) with alterable axial length over an 8-Diopter range. Figure 19 illustrates that there is a significant ($r^2 > 0.99$) linear relationship between the static SE value (x) calculated by the instrument itself and the dynamic measurement ring diameter (y, in pixel, measured by the LabVIEW program), which also supports that there exists a linear relationship between SE and the movement of the Badal lens. A simple equation is therefore created to convert the measurement ring diameter into SE value or, depending on the stimulus configuration, accommodation response.

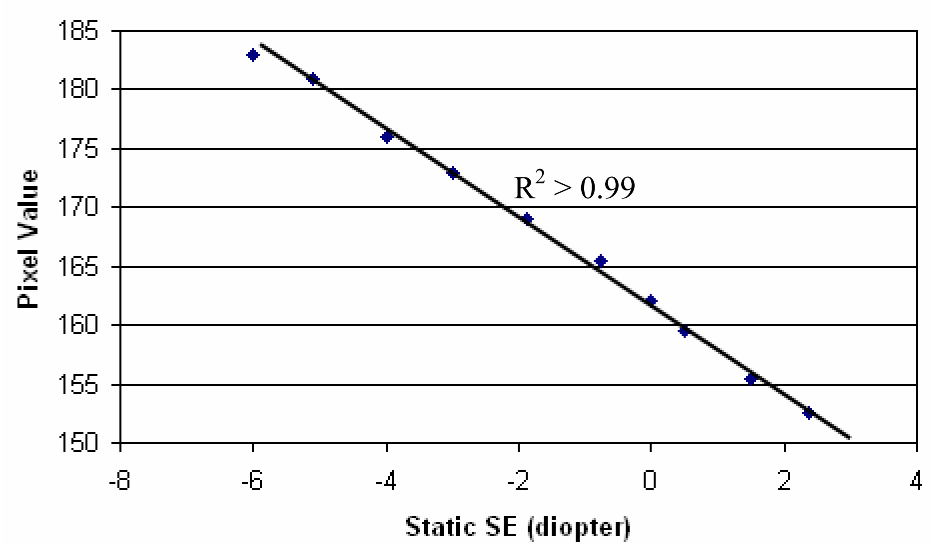


Figure 19: Relationship between static SE value and the diameter of the ring

However, as the setting of the original NTSC signal has to be adjusted to maximize the brightness of the measurement ring image for different individuals, the simultaneous static and dynamic accommodative measures via the model eye under different brightness setups indicate that the intercept of the conversion equation changes with the change of the setup but the slope of the equation remains fairly fixed at a certain pixel value. As a result, a simple calibration procedure is developed to create a proper conversion equation for different subjects. Specifically, as the slope of the equation is fixed, the correct intercept of the equation is calculated by inputting the averaged diameter of the measurement ring and the static SE value after the simultaneous static and dynamic accommodative measures are performed for a subject at any viewing conditions after the brightness level of his or her NTSC signal is set. By doing so, the resulting equation is expected to be proper to transfer the pixel results to SE value for this subject. Also, by performing the calibration procedure, it helps ensure the appropriateness of using the pixel value of 20 as the threshold level to detect the ring edges, because a fixed threshold level will detect edges at different points when the brightness of the image is changed, and vice versa. In other words, the effect of different threshold levels on edge detection is the same as that of different brightness setups of the image. As such, the calibration procedure takes into account the possibility of the change of the conversion equation when different threshold levels are chosen.

To summarize, the methodology of developing a LabVIEW program to measure the accommodation process via the modified autorefractor is described. Last but not least, in order to synchronize the recording of accommodation and the trigger of accommodation (i.e., the flipping of the mirror), the program includes a function to capture the point of time when the mirror is manually flipped, which helps define the start point of stimulus change and facilitates data analysis. As the program measures the SE value at a resolution of < 0.0001 Diopters and a sampling frequency of 60 Hz, the raw data (the blue dots in the upper graph in Figure 20) have to be preprocessed so as to extract reliable information in regards to the recorded accommodative status.

3.3.4 Data processing

After developing the measure of accommodation via autorefractors, vision researchers have started utilizing this technique to study the dynamic aspects of accommodation (Chat and Edwards, 2001, Heron, et al., 2002, Mallen et al., 2001, Rucker and Kruger, 2004, Sun et al., 1988, Wolffsohn, et al., 2001, 2002). 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 manual selection, in other words visual detection, of the critical points during accommodation (e.g., the onset and offset of accommodation) (Heron, et al., 2002, Rucker and Kruger, 2004, Wolffsohn, et al., 2001, 2002). The deficit of manual selection is that it provides an unreliable detection of the critical points which prevents the results in one study from comparing with those in other studies. Thus, in order to overcome the weakness of manual selection, a mathematical procedure is developed to preprocess the data and facilitate the detection of the critical points (Figure 20).

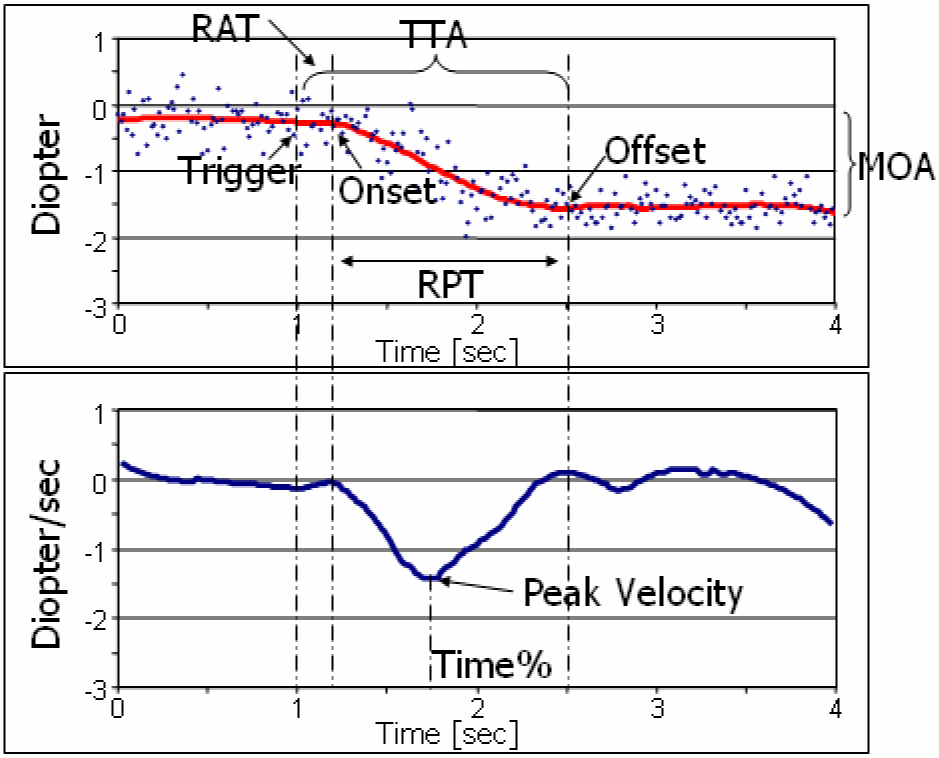


Figure 20: Sample accommodation process and its velocity curve (Redrawn from Fig. 5)

Specifically, a 4th order Savitzky-Golay filter is applied to the raw data to smooth the data with the size of a sliding window at (2*60+1)[7]. After obtaining the smoothed data, the onset and offset of accommodation are determined mathematically via a velocity curve which, by definition, is the movement speed of the focus of the eye during accommodation and is calculated by dividing the difference between one preceding and on succeeding SE value by the time interval between them (i.e., 2*1/60s). The lower graph in Figure 20 illustrates the velocity curve based on the smoothed data, which is further smoothed by another 4th order Savitzky-Golay filter with the size of a sliding window at (2*20+1). The reason for using Savitzky-Golay filtering on both the raw data and the raw velocity data is to remove noise related to high-frequency movement artifacts while preserving abrupt level changes. As Savitzky-Golay filtering utilizes polynomial regression to find the best-fit curve at each raw data point by considering the surrounding

[7] "2*60 + 1" means a total of 121 points, i.e., the point to be smoothed plus 60 points before/after that.

data (the range of the data is controlled by the size of a sliding window), a large window size helps smooth data with high-frequency noise. As a result, a window of (2*60+1) points and that of (2*20+1) points are applied to the raw and velocity data, respectively, based on their own data distribution. Hence, the onset and offset of accommodation are determined by the two minimum velocities before and after the peak velocity. Along with the known time point when accommodation is triggered (i.e., the time point when the mirror is flipped and is recorded via the synchronization function of the program), reaction time, the response time, and the total time to accommodate can be obtained as well as the magnitude of accommodation, the peak velocity, and the percentage of time when the velocity reaches its maximum.

In summary, by means of LabVIEW programming and the filtering mechanisms, the study provided a fairly replicable technique to assess dynamic accommodation. According to the pilot test designed to evaluate the experimental setup, the reliability of the measure of accommodation via the modified autorefractor was greater than 0.90 (measured by the Intra-class Correlation, ICC), which supported the use of the instrument along with LabVIEW programming to the study of one’s accommodative status.

3.4 Experiment setup 3 – Apparatus and test site

3.4.1 Apparatus

As mentioned in the previous sections, the mirror machine, the modified Shin-Nippon SRW-5000 autorefractor, and a LabVIEW program were used to assess one's accommodative status. A complete list of equipment used in the study is shown below:

1. Bausch & Lomb ® Vision Tester (for visual acuity and color-blindness test)
2. Vistech ® Chart V6500 version B (for contrast sensitivity test)
3. Laptop PC (with PowerPoint slides of Maltese Cross in different chromaticities)
4. Several ND filters (to control the luminance of the laptop screen)
5. Fixation board (as the far target)
6. The mirror machine (with an air tank to flip the mirror)
7. The modified Shin-Nippon SRW-5000 autorefractor
8. Dell PC (connected with the autorefractor via an NI PCI-1407 Image Acquisition Card and used to collect data via a LabVIEW program)
9. Additional lighting (to provide the far target with a constant luminance condition at 50 cd/m^2)
10. Photometer luminance meter (Model: Minolta CS-100)
11. Head & chin rest
12. Adjustable height chair

3.4.2 Test site

The study was conducted in the Visual Controls Laboratory at 519A Whittemore Hall, Virginia Tech. Figures 7-9 illustrate the setup of the mirror machine and the near and far targets, and Figure 21 shows the actual test conditions. In order to assess the effects of light on accommodation, the near (the laptop) and far (the fixation board) targets acted as a sole light source. No ambient lighting was provided. The luminance of the laptop screen was set at two levels (i.e., 100 and 20 cd/m^2). To facilitate the fixation on the far target, additional lighting was provided underneath the target to set the luminance of the far target at 50 cd/m^2 (measured at the eye level of the participant).

Figure 21: Real test conditions

3.5 Procedures

3.5.1 The screening session

As mentioned earlier, each participant was required to have no eye disease (especially, color blindness) or eye surgery in the past and had normal vision at 20/20 in at least one of the eyes. Due to the interference between the autorefractor and normal spectacles, corrected vision was acceptable only if contact lenses were worn. To ensure the qualification of the participant, a screening session was held prior to the actual test session under the normal lighting conditions, which took place after the participant had signed an IRB-approved informed consent form (See Appendix: Consent Form and Questionnaire) and completed a questionnaire regarding to their personal information (See Appendix: Consent Form and Questionnaire). During the screening session, a test of static visual acuity and color blindness was performed for each of the eyes via the Bausch & Lomb ® Vision Tester (Figure 22) to ensure that the participant had no worse than normal vision (20/20) and no color blindness. Then, his or her static contrast sensitivity was tested for each of the eyes via the Vistech ® Contrast Sensitivity Chart (Figure 23). The results of his or her contrast sensitivity were used to plot a contrast sensitivity curve for each of the eyes. So long as the curve fell within the normal range of contrast sensitivity for adulthood, it can be suggested that the participant's eyes did not have symptoms of eye diseases such as glaucoma and cataract.

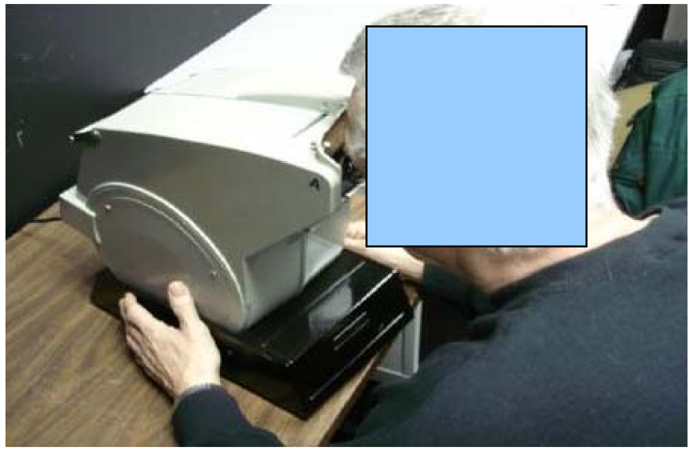


Figure 22: The static visual acuity test

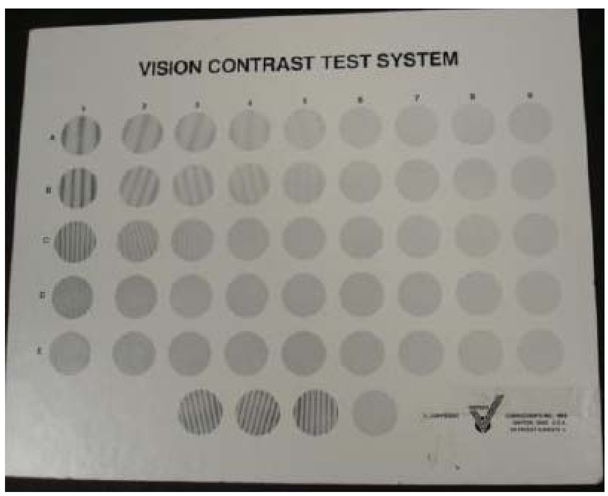


Figure 23: The contrast sensitivity chart

The protocol used in the static visual acuity test was "Please put your forehead against the forehead rest on the instrument and look through the mirror. Assuming you can see the images behind the mirror, in the big sign at the top, the No. 1 sign, do you see a large black checkerboard? If so, where is the checkerboard, top, right, left, or down? In the No. 2 sign, where is the checkerboard? Number 3? Number 4? Etc." The protocol used in the color blindness test was "Please look through the mirror and tell me the numbers displayed within the left and right signs."

As for the static contrast sensitivity test, the participant was asked to cover one of their eyes by a black plate and look at the chart at approximately 70 cm away. The protocol used was "Your task is to read across each row, starting with row A, patch one, and call out whether the patch is oriented to the left, right, straight up or down or patches are very low in contrast and you may not see any bars in these patches. If this is the case, simply answer 'blank.' However, if you do see something in a patch but you are not sure of the orientation, you are allowed to guess." After the participant finished all of the rows, the experimenter would check the numbered circle in each column on the record sheet, which corresponded to the highest numbered patch he or she saw correctly in each row of the chart. After connecting the circles, the contrast sensitivity curve was achieved.

3.5.2 The actual test session

After the screening session, qualified participants were asked to sit in a chair in front of the autorefractor and place their forehead and chin firmly against the forehead and chin rest (Figure 21). An occluder was used to limit the amount of light reaching the eyes so that the far and near targets were seen monocularly when both the eyes were open. Since the focus of the study was to assess the accommodative ability of the eye for different age groups, it did not matter which of the two eyes to be tested as long as it passed the screening test and was qualified for the study. Similar situations also occurred in the literature, in which researchers usually reported the results of the accommodative ability of the eye without specifying which of the two eyes was tested (Johnson, 1976, Jackson, et al., 1999, Wolffsohn, et al., 2001, 2004, Wilson, et al., 2002, Rucker and Kruger, 2004). As a result, the measure of accommodation for each participant was conducted by only testing the eye that had a better performance in the screening tests, which also helped reduce the difficulty in finding qualified participants for the study.

Before starting the formal tests, each participant was familiarized with the layout of the apparatus, and the change from the far target to the near target triggered by the mirror machine was explained. His or her static refractive errors were measured, and the results were used to calibrate the LabVIEW program and to ensure that no abnormal astigmatism was present (> 0.5 Diopters, Heron, et al., 2002). During recording, encouragement was given which was reinforced when high quality records were being produced, and the participant was discouraged from blinking during recording (Heron, et al., 2002). All of the participants were given plenty of practice to familiarize themselves with the task before recording commenced. The training session would be stopped only if the expected pattern of accommodation (e.g., the magnitude of accommodation) based on that of a typical eye at a similar age was recorded under the sample stimulus. That is, for a younger participant, a clear move of the focus of the eye from one target to the other should be recorded, while an older participant should exhibit less change.

The formal session would begin after sufficient training had been taken by each participant. A push-up method (Hamasaki, et al., 1956) along with the modified autorefractor was used to assess both the subjective and objective nearest point the participant could focus on. A Landolt's C target that corresponded in size to visual acuity of 20/20 was loaded in the middle of the laptop, and the participant was required to focus on the Landolt's C. The target was then slowly moved towards the participant along a track attached to the mirror machine until he or she reported first sustained blur. The point where he or she reported first sustained blur was recorded. The recorded point was the subjective nearest point of the eye in that research suggested that the push-up method was contaminated by the effects of the depth of focus[8] (Hamasaki, et al., 1956). In other words, the point reported by the participant was closer to the eye than the actual point where maximum accommodation is achieved. As such, the modified autorefractor was used to monitor the change of the Spherical Equivalent value during the push-up process, and the objective nearest point was detected when the SE value became relatively constant. All of the measurements were repeated twice, and the averaged location was used to place the near target for the Condition 1 test. The protocol used in the push-up test was "Please focus on the Landolt's C in the middle of the laptop and keep it as clear as possible. I'll start to move the target towards you. If the C starts blurring, please report to me."

[8] Depth of focus: the distance which the target can be moved while maintaining an acceptably sharp image without refocusing the lens.

Each participant started the measure of accommodation under either Condition 1 or 2, randomly selected. For each condition, there were a total of four accommodation tests (i.e., 2 chromaticities of the target * 2 brightness levels of the laptop screen). The sequence of the four tests was also randomized, and the measure of accommodation under each test was performed twice for each participant. After each measure, a one-minute break was given. The protocol used was: "Now, we'll start the measurement. Please make sure to place your chin on the chin rest and your forehead firmly against the forehead rest. Please look forward onto the center of the far target and focus on it. Currently, you can still blink your eyes at any time, and I will tell you know when I am about to change the targets… Ok, now get set and stop blinking your eyes and focus on the current target. I will flip the mirror soon and keep in mind to try your best to focus on the new target… Ok, great job! You can relax now."

After both conditions were finished, the experiment was over, and the participant was thanked and compensated. All of the data processing was post hoc and based on the method described in Section 3.3.4 Data processing.

3.5.3 Pilot testing

After the LabVIEW program was developed, pilot testing was conducted with several volunteers following exactly the procedures as aforementioned. Based on the test, corrections to the program were made, and the author gained sufficient experience on how to conduct and manipulate the experiment. The data colleted in the pilot test was explored, and a detailed method of data processing was developed thereafter. The pilot results also suggested that the reliability of the measure of accommodation via the modified autorefractor and the LabVIEW program was greater than 0.90, as measured by the Intra-class Correlation (ICC) on the extracted values of the reaction and response times.

3.6 Experiment design

In order to assess the global and specific effects of age group, light intensity, and light chromaticity on the dynamic accommodative characteristics, multivariate analysis of variance (MANOVA) and univariate analysis of variance (ANOVA) were utilized to analyze the data. For the univariate ANOVA, a 3x2x2 mixed-factor design was used (Table 2).

Table 2: Experiment design

Younger Group	Daytime		Nighttime	
	Blue	Red	Blue	Red
Middle-aged Group	Daytime		Nighttime	
	Blue	Red	Blue	Red
Older Group	Daytime		Nighttime	
	Blue	Red	Blue	Red

The independent variables of the study included:

a. Age group: 3 levels (i.e., younger, middle-aged, older);
b. Intensity of light: 2 levels (i.e., daytime at 100 cd/m^2 vs. nighttime at 20 cd/m^2);
c. Chromaticity of light: 2 levels (i.e., red vs. blue).

The age group (three levels) was a between-subjects variable, while the intensity of light (two levels) and the chromaticity of light (two levels) were within-subject variables. In the analysis, the three variables were assumed to be fixed-effect factors, while the subject variable was a random-effect factor.

The dependent variables of the study were based on the six parameters extracted from the accommodation process (Figure 5, see Page 18 for detailed definitions):

a. The magnitude of accommodation (MOA) in Diopter;
b. Reaction time (RAT) in millisecond;
c. The response time index (RTI) in millisecond per meter (derived from the division of the response time (RPT) by the actual accommodative distance);
d. The accommodation time index (ATI) in millisecond per meter (derived from the division of the total time to accommodate (TTA) by the actual accommodative distance);
e. The peak velocity (PV) in Diopter per second;
f. The percentage of time to reach the peak velocity (Time%) in percentage.

Compared with the literature (e.g., Duane, 1912, Sun, et al., 1988, Mordi and Ciuffreda, 1998, Ciuffreda, et al., 2000, and Heron, et al., 2002), MOA and RAT were often used to describe the static and dynamic aspects of an accommodation process. In order to better understand the speed of accommodation, this study developed four new parameters (i.e., RTI, ATI, PV, and Time%) on the basis of the recorded accommodation process (Figure 5). Additionally, with the consideration of the age-related accommodation loss, the response time (RPT) and the total time to accommodate (TTA) were further converted to index values (i.e., RTI and ATI, respectively).

Note that while each participant went through two test conditions (i.e., Condition 1: the adjustable stimulus, and Condition 2: the fixed stimulus), the condition effect was not considered to be an independent variable. Initially, the purpose of having the two conditions in the experiment was to assess the distance effect on accommodation (i.e., the distance to place the near target). The results of the push-up experiment, and the measure of the dynamic accommodation responses for the three age groups indicated that participants' accommodative performances under these two conditions did not differ to a significant extent (Figure 24). A possible explanation was that the two conditions actually created a similar stimulus for accommodation, in that, both of the conditions had triggered a maximum amount of one's accommodative ability. As such, the condition effect was not included further as an independent variable. Since the current study was designed to simulate one's accommodative performance on focusing on the dashboard (a fixed location), statistical analysis was performed only on the data measured under Condition 2, that is, the fixed location of the near target (70 cm).

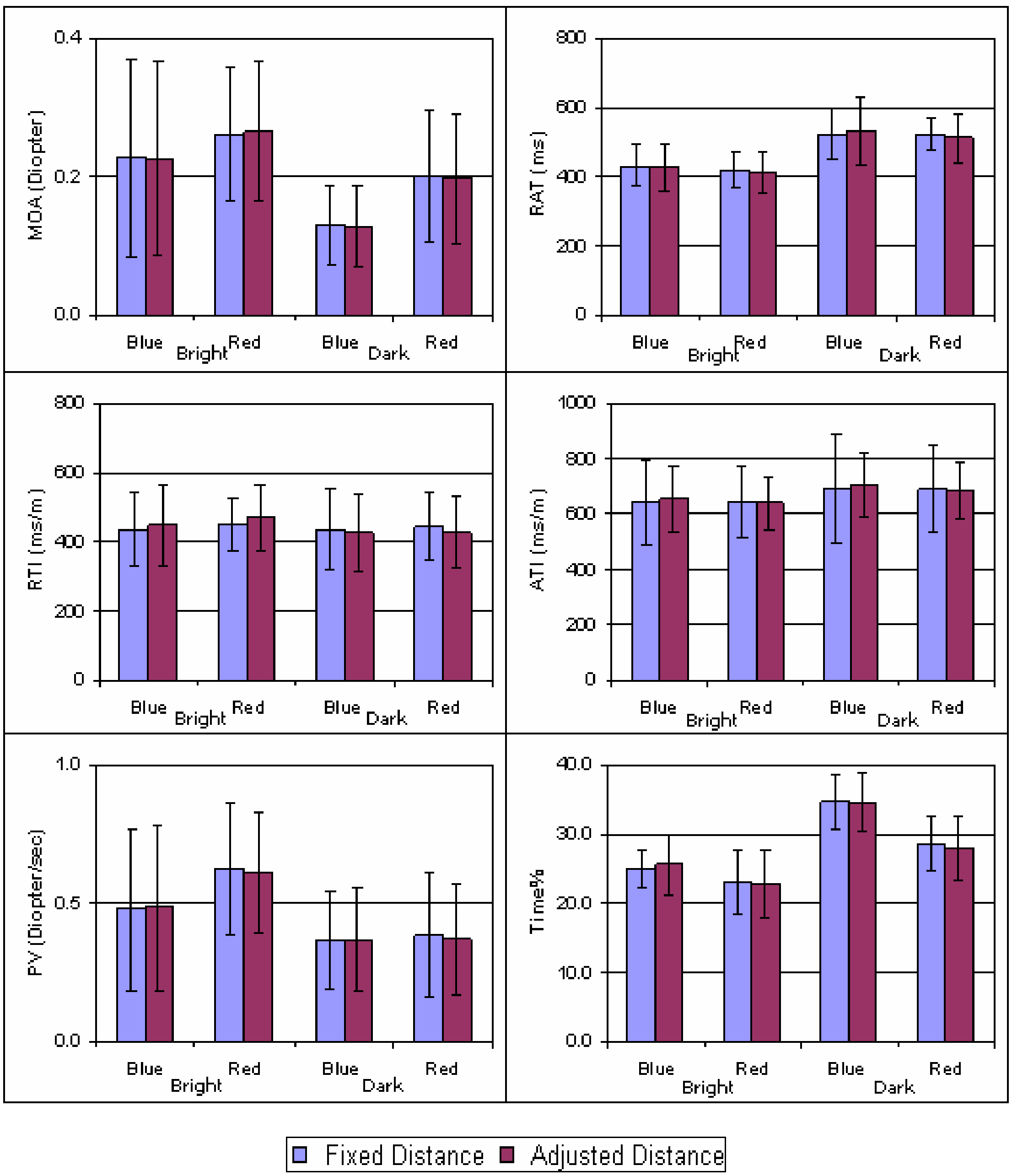


Figure 24: Means and SDs of the six parameters under the two test conditions

3.7 Data analysis

SAS 9.1.3 was utilized for the data analysis. Based on the experiment design (Table 2), a mixed-factor multivariate analysis of variance (MANOVA) was conducted where age was a between-subjects factor, and light intensity and light chromaticity were within-subject factors. Using the Wilks' Lambda test, the MANOVA allowed for determination of which factors and relevant interactions had significant effects on the six dependent variables as a whole (i.e., MOA, RAT, RTI, ATI, PV, and Time%). This global assessment was used to address the four main hypotheses of the study. In the present study, effects were considered significant when $p < 0.05$ (throughout the data analysis). Since a global effect did not contain information about how each of the dependent variables was affected, a statistically significant main effect or interaction effect found in the MANOVA test triggered subsequent univariate analysis of variance (ANOVA) to elucidate the effect on each of the dependent variables.

Thus, following the MANOVA test, subsequent univariate ANOVAs (mixed-factor design) were conducted separately for each dependent variable. The statistical model of a three-way mixed-factor ANOVA is shown below:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_{l(i)} + \alpha\beta_{ij} + \alpha\gamma_{ik} + \beta\gamma_{jk} + \beta\theta_{jl(i)} + \gamma\theta_{kl(i)} + \alpha\beta\gamma_{ijk} + \beta\gamma\theta_{jkl(i)} + \varepsilon_{m(ijkl)}$$

$$E(MS_A) = bcn\delta_\alpha^2 + abc\delta_\theta^2 + \delta_\varepsilon^2$$

$$E(MS_{S(A)}) = abc\delta_\theta^2 + \delta_\varepsilon^2$$

$$E(MS_B) = acn\delta_\beta^2 + c\delta_{\beta\theta(\alpha)}^2 + abc\delta_\theta^2 + \delta_\varepsilon^2$$

$$E(MS_C) = abn\delta_\gamma^2 + b\delta_{\lambda\theta(\alpha)}^2 + abc\delta_\theta^2 + \delta_\varepsilon^2$$

$$E(MS_{AB}) = cn\delta_{\alpha\beta}^2 + c\delta_{\beta\theta(\alpha)}^2 + abc\delta_\theta^2 + \delta_\varepsilon^2$$

$$E(MS_{AC}) = bn\delta_{\alpha\gamma}^2 + b\delta_{\lambda\theta(\alpha)}^2 + abc\delta_\theta^2 + \delta_\varepsilon^2$$

$$E(MS_{BC}) = an\delta_{\beta\gamma}^2 + \delta_{\beta\lambda\theta(\alpha)}^2 + abc\delta_\theta^2 + \delta_\varepsilon^2$$

$$E(MS_{BS(A)}) = c\delta^2_{\beta\theta(\alpha)} + abc\delta^2_{\theta} + \delta^2_{\varepsilon}$$

$$E(MS_{CS(A)}) = b\delta^2_{\lambda\theta(\alpha)} + abc\delta^2_{\theta} + \delta^2_{\varepsilon}$$

$$E(MS_{ABC}) = n\delta^2_{\alpha\beta\gamma} + \delta^2_{\beta\lambda\theta(\alpha)} + abc\delta^2_{\theta} + \delta^2_{\varepsilon}$$

$$E(MS_{BCS(A)}) = \delta^2_{\beta\lambda\theta(\alpha)} + abc\delta^2_{\theta} + \delta^2_{\varepsilon}$$

where μ is the overall mean; A, α, i, a (=3) denote the age effect; B, β, j, b (=2) denote the intensity effect; C, γ, k, c (=2) denote the color effect; S, θ, l, n (=10) denote the number of the subjects in each of the age groups; ε, m represent the random error.

Table 3: Source and Error terms for three-way mixed-factor ANOVA

Source	**df**	**SS**	**MS**	**F**
Between				
Age	a-1	SS_A	MS_A	$MS_A / MS_{S(A)}$
Subject(Age)	a(n-1)	$SS_{S(A)}$	$MS_{S(A)}$	
Within				
Intensity	b-1	SS_B	MS_B	$MS_B / MS_{BS(A)}$
Color	c-1	SS_C	MS_C	$MS_C / MS_{CS(A)}$
Age*Intensity	(a-1)(b-1)	SS_{AB}	MS_{AB}	$MS_{AB} / MS_{BS(A)}$
Age*Color	(a-1)(c-1)	SS_{AC}	MS_{AC}	$MS_{AC} / MS_{CS(A)}$
Intensity*Color	(b-1)(c-1)	SS_{BC}	MS_{BC}	$MS_{BC} / MS_{BCS(A)}$
Intensity*Subject(Age)	a(b-1)(n-1)	$SS_{BS(A)}$	$MS_{BS(A)}$	
Color*Subject(Age)	a(c-1)(n-1)	$SS_{CS(A)}$	$MS_{CS(A)}$	
Age*Intensity*Color	(a-1)(b-1)(c-1)	SS_{ABC}	MS_{ABC}	$MS_{ABC} / MS_{BCS(A)}$
Intensity*Color*Subject(Age)	a(b-1)(c-1)(n-1)	$SS_{BCS(A)}$	$MS_{BCS(A)}$	
Total	abcn-1	SS_{total}		

Based on the model, F tests (Table 3) were used for hypothesis testing with a significance level of $p < 0.05$. Tukey’s Honestly Significant Difference (HSD) test was also conducted for post-hoc comparisons to identify differences in the effects of different levels of the independent variables.

Last but not least, in order to verify the assumptions of MANOVA and ANOVA, all of the data were evaluated for normality (via Shapiro-Wilk W Test), sphericity (via Mauchly's sphericity test), and potential outliers (via box plot). The results indicated no significant violation of the assumptions.

4. RESULTS

The hypotheses of the study were: 1) the age-related changes of the eye will lead to the change of the dynamic accommodative performance; 2) light of different intensities will influence one's dynamic accommodative performance; 3) light of different chromaticities will result in different dynamic accommodative performances; and 4) light of different intensities and chromaticities will change the age-related accommodation loss. In order to test the hypotheses, a three-way mixed-factor MANOVA test was first conducted to assess the global effects of aging, light intensity, light chromaticity, and their interactions on the dynamic accommodative performance (parameterized by MOA, RAT, RTI, ATI, PV, and Time%). In general, the main effects of the three independent variables and their two-way interactions were all of statistical significance (Table 4). Therefore, subsequent univariate mixed-factor ANOVA tests were performed to elucidate the effects of aging, light intensity, light chromaticity, and their interactions on each of the dependent variables.

The results of the MANOVA and ANOVA tests are reported in Section 4.1 and Section 4.2, respectively. Section 4.3 then describes the logistic modeling of the accommodation responses measured in the present study, and Section 4.4 covers the results of the validation experiment.

4.1 The MANOVA test

The purpose of conducting a MANOVA was to have a global assessment of the effects of the independent variables on the dynamic accommodative performance. This was because it was not clear at this time which dynamic aspects (i.e., MOA, RAT, RTI, ATI, PV, and Time%) were most sensitive to aging, and different intensities or chromaticities of light. The results of the MANOVA test are summarized in Table 4. Overall, the accommodative performance was significantly affected by age ($F_{(24,32)}$=21.71, P<.0001), light intensity ($F_{(12,16)}$=85.20, P<.0001), and light chromaticity ($F_{(12,16)}$=43.67, P<.0001). Statistically significant interaction effects were also found between age and light intensity ($F_{(24,32)}$=6.67, P<.0001), age and light chromaticity ($F_{(24,32)}$=2.81, P=0.0034), and light intensity and light chromaticity ($F_{(12,16)}$=2.96, P=0.0225). As such, subsequent univariate ANOVAs were conducted thereafter on each dependent variable.

Table 4: MANOVA test for the general effects of age, light intensity and chromaticity

Source	**Error**	**Wilks' Lambda**	**F Value**	**Prob > F**
Age	Subject(Age)	0.00	$F_{(24,32)}$=21.71	**<.0001**
Intensity	Intensity*Subject(Age)	0.02	$F_{(12,16)}$=85.20	**<.0001**
Color	Color*Subject(Age)	0.03	$F_{(12,16)}$=43.67	**<.0001**
Age*Intensity	Intensity*Subject(Age)	0.03	$F_{(24,32)}$=6.67	**<.0001**
Age*Color	Color*Subject(Age)	0.10	$F_{(24,32)}$=2.81	**0.0034**
Intensity*Color	Intensity*Color* Subject(Age)	0.31	$F_{(12,16)}$=2.96	**0.0225**
Age*Intensity*Color	Intensity*Color* Subject(Age)	0.21	$F_{(24,32)}$=1.60	0.1056

4.2 The univariate ANOVA tests

In order to provide better understanding of how the accommodative characteristics were influenced by aging, light intensity, and light chromaticity, each of the six dependent variables (i.e., MOA, RAT, RTI, ATI, PV, and Time%) was analyzed separately using univariate mixed-factor repeated-measure ANOVA.

4.2.1 The univariate ANOVA test for the magnitude of accommodation (MOA)

The results of the univariate ANOVA test for the magnitude of accommodation are summarized in Table 5. The magnitude of accommodation is defined as the difference of the average Spherical Equivalent values between the two steady focus levels before and after accommodation (Figure 5). In general, different age groups, light intensities, and light chromaticities all led to statistically significant changes of the magnitude of accommodation. The interaction effect between age group and light intensity and that between light intensity and light chromaticity were also of statistical significance.

Table 5: ANOVA test for the magnitude of accommodation

Source	**Error**	**F Value**	**Prob > F**
Age	Subject(Age)	$F_{(4,52)}=45.21$	**<.0001**
Intensity	Intensity*Subject(Age)	$F_{(2,26)}=164.34$	**<.0001**
Color	Color*Subject(Age)	$F_{(2,26)}=7.91$	**0.0021**
Age*Intensity	Intensity*Subject(Age)	$F_{(4,52)}=16.47$	**<.0001**
Age*Color	Color*Subject(Age)	$F_{(4,52)}=0.20$	0.9397
Intensity*Color	Intensity*Color* Subject(Age)	$F_{(2,26)}=5.09$	**0.0136**
Age*Intensity*Color	Intensity*Color* Subject(Age)	$F_{(4,52)}=2.52$	0.0522

4.2.1.1 The main effects

a) Age group main effect

Overall, aging resulted in decreased magnitude of accommodation. This effect was statistically significant ($F_{(4,52)}$=45.21, P<.0001). The means and standard deviations of the magnitude of accommodation for the three age groups are listed in Table 6 and illustrated in Figure 25. A Tukey post-hoc test indicated that the magnitude of accommodation was significantly different across all of the age groups (Table 7).

Table 6: Descriptive statistics of age main effect on MOA

Age Group	MOA Mean (Diopter)	Standard Deviation
Younger	1.137	0.205
Middle-aged	1.005	0.277
Older	0.204	0.112

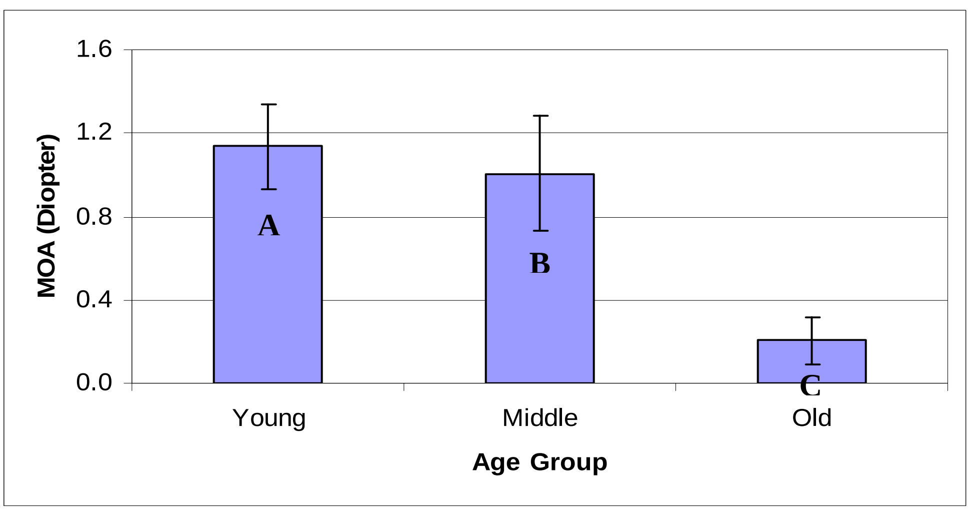


Figure 25: Means and SDs of MOA across the three age groups (Different letters signify significant differences at the p < 0.05 level, see Table 7.)

Table 7: Tukey's HSD test of age main effect at alpha=0.05

LSmean – LSmean	Diff	Lower CL Diff	Upper CL Diff	Pr > |t|
Younger – Middle-aged	0.132	0.111	0.153	**<.0001**
Younger – Older	0.932	0.911	0.953	**<.0001**
Middle-aged – Older	0.801	0.779	0.822	**<.0001**

b) Light intensity main effect

In general, the magnitude of accommodation was significantly different under the two light intensity levels ($F_{(2,26)}$=164.34, P<.0001), and light of higher intensity resulted in a larger magnitude of accommodation (Table 8, Figure 26).

Table 8: Descriptive statistics of light intensity main effect on MOA

Light Intensity	MOA Mean (Diopter)	Standard Deviation
Bright (100 cd/m^2)	0.918	0.495
Dark (20 cd/m^2)	0.646	0.383

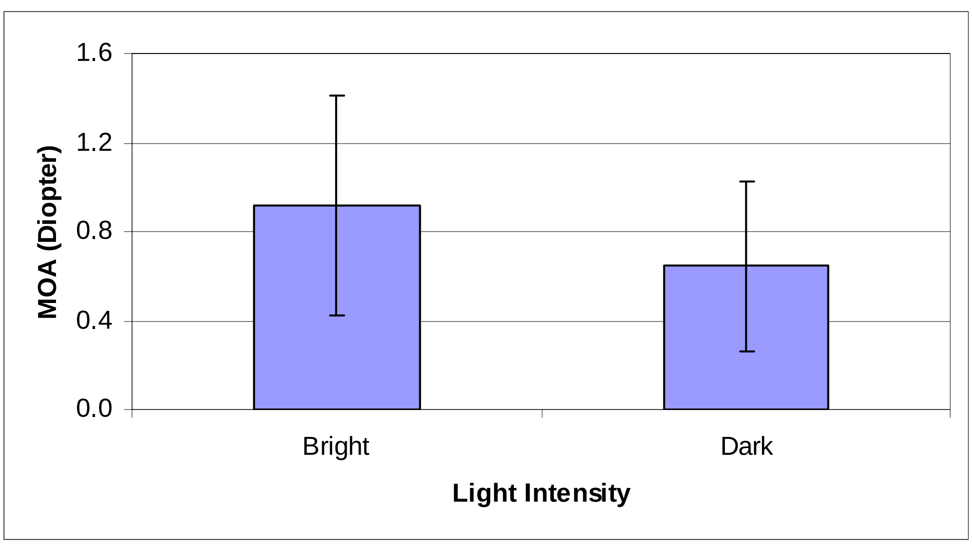


Figure 26: Means and SDs of MOA for the two light intensity levels

c) Light chromaticity main effect

Under the two light chromaticity levels, the magnitude of accommodation was significantly different ($F_{(2,26)}$=7.91, P=0.0021). When viewing the red image, the participants had a slightly higher magnitude of accommodation than when viewing the blue one (Table 9, Figure 27).

Table 9: Descriptive statistics of light chromaticity main effect on MOA

Light Intensity	MOA Mean (Diopter)	Standard Deviation
Blue	0.751	0.462
Red	0.813	0.462

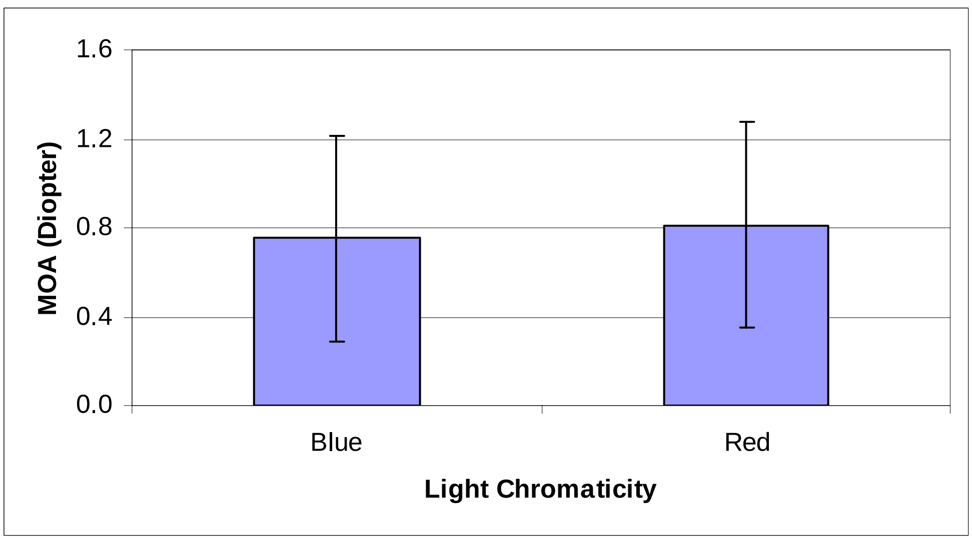


Figure 27: Means and SDs of MOA for the two light chromaticity levels

4.2.1.2 The interaction effects

a) Age x light intensity effect

The interaction between age and light intensity was found to be statistically significant ($F_{(4,52)}$=16.47, P<.0001). Table 10 and Figure 28 elaborate that the younger and middle-aged participants had similar MOA under the daytime conditions, while the middle-aged counterparts had a lower MOA than the younger ones when the intensity of light was decreased. Moreover, the older participants did not have as much decline of the magnitude of accommodation under the nighttime conditions as the other two groups did.

Table 10: Descriptive statistics of age x light intensity effect on MOA

Interaction	MOA Mean (Diopter)	Standard Deviation
Younger, Bright	1.271	0.138
Younger, Dark	1.003	0.171
Middle-aged, Bright	1.239	0.120
Middle-aged, Dark	0.771	0.167
Older, Bright	0.244	0.121
Older, Dark	0.165	0.086

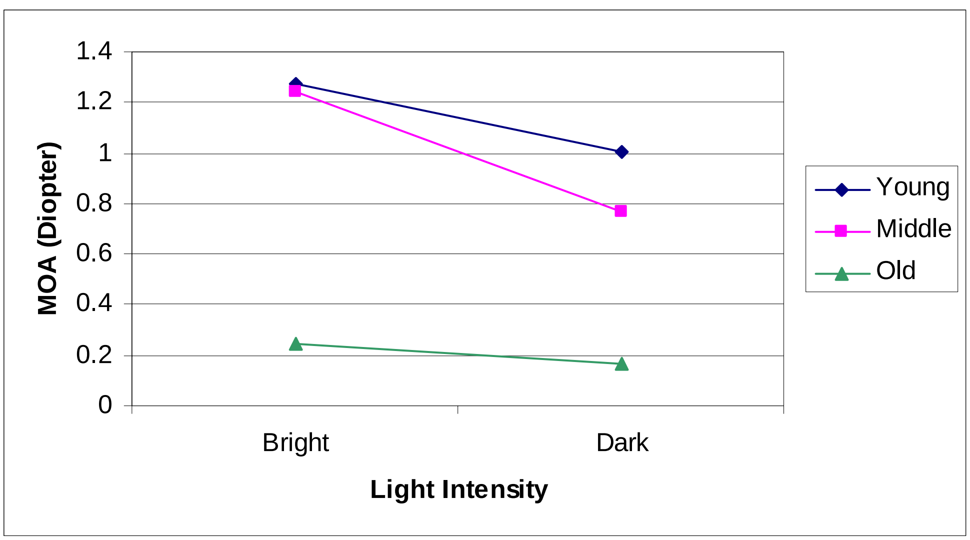


Figure 28: Age x light intensity on MOA

b) Age x light chromaticity effect

No statistically significant interaction effect was found between age and light chromaticity ($F_{(4,52)}$=0.20, P=0.9397, Figure 29).

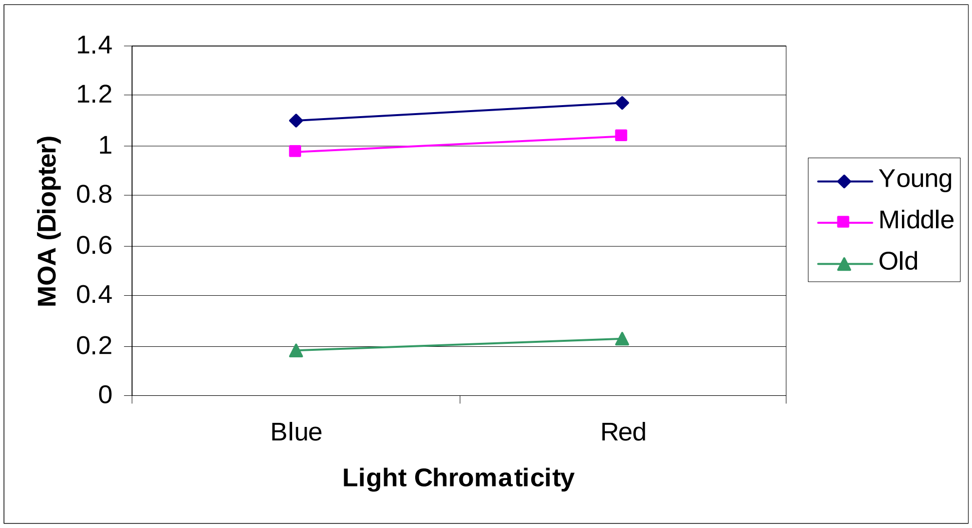


Figure 29: Age x light chromaticity on MOA

c) Light intensity x light chromaticity effect

The interaction between light intensity and light chromaticity was statistically significant ($F_{(2,26)}$=5.09, P=0.0136). In general, under the daytime conditions, the two light chromaticity levels resulted in similar magnitude of accommodation, while under the nighttime conditions, MOA for the blue image was lower than that for the red image (Table 11, Figure 30).

Table 11: Descriptive statistics of light intensity x light chromaticity effect on MOA

Interaction	MOA Mean (Diopter)	Standard Deviation
Bright, Blue	0.902	0.497
Bright, Red	0.935	0.496
Dark, Blue	0.600	0.371
Dark, Red	0.692	0.393

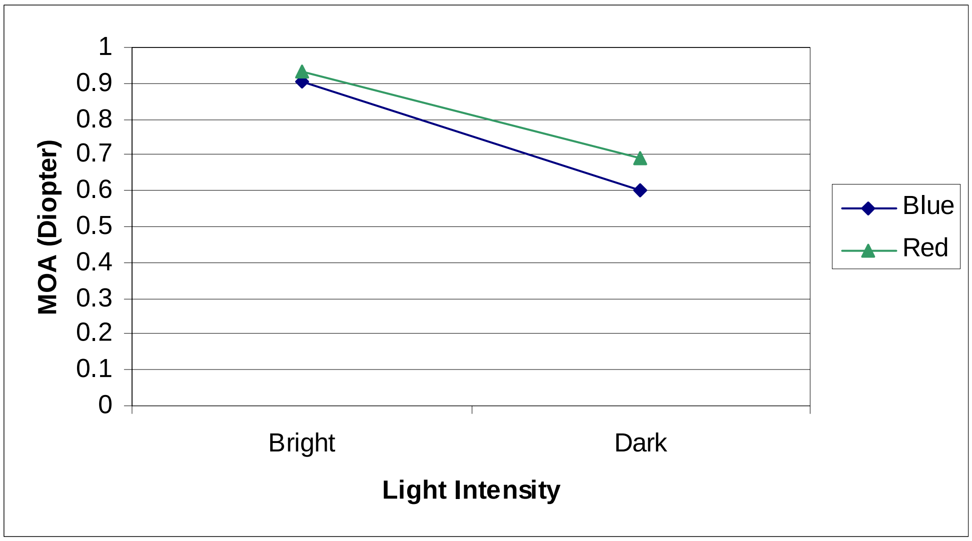


Figure 30: Light intensity x light chromaticity on MOA

4.2.1.3 Summary of the ANOVA test on MOA

To summarize, the advancing of age, decreased light intensity, and bluish light chromaticity all led to the decline of the magnitude of accommodation.

4.2.2 The univariate ANOVA test for reaction time (RAT)

The results of the univariate ANOVA test for reaction time are summarized in Table 12. Reaction time is defined as the time interval between the known instant of stimulus change and the time at which the response just starts to change from the initial steady state level (Figure 5). In general, different age groups, light intensities, and light chromaticities all resulted in statistically significant changes of reaction time. The only significant interaction effect occurred between age group and light intensity.

Table 12: ANOVA test for reaction time

Source	**Error**	**F Value**	**Prob > F**
Age	Subject(Age)	$F_{(4,52)}$=32.48	**<.0001**
Intensity	Intensity*Subject(Age)	$F_{(2,26)}$=57.91	**<.0001**
Color	Color*Subject(Age)	$F_{(2,26)}$=9.62	**0.0007**
Age*Intensity	Intensity*Subject(Age)	$F_{(4,52)}$=8.17	**<.0001**
Age*Color	Color*Subject(Age)	$F_{(4,52)}$=1.34	0.2674
Intensity*Color	Intensity*Color* Subject(Age)	$F_{(2,26)}$=0.81	0.4554
Age*Intensity*Color	Intensity*Color* Subject(Age)	$F_{(4,52)}$=1.01	0.4115

4.2.2.1 The main effects

a) Age group main effect

Overall, aging led to an increase of reaction time. This aging effect was statistically significant ($F_{(4,52)}$=32.48, P<.0001). The means and standard deviations of reaction time for the three age groups are shown in Table 13 and illustrated in Figure 31. A Tukey post-hoc test indicated that reaction time was significantly different across all of the three age groups (Table 14).

Table 13: Descriptive statistics of age main effect on RAT

Age Group	RAT Mean (ms)	Standard Deviation
Younger	238.247	37.319
Middle-aged	380.940	53.528
Older	472.686	75.153

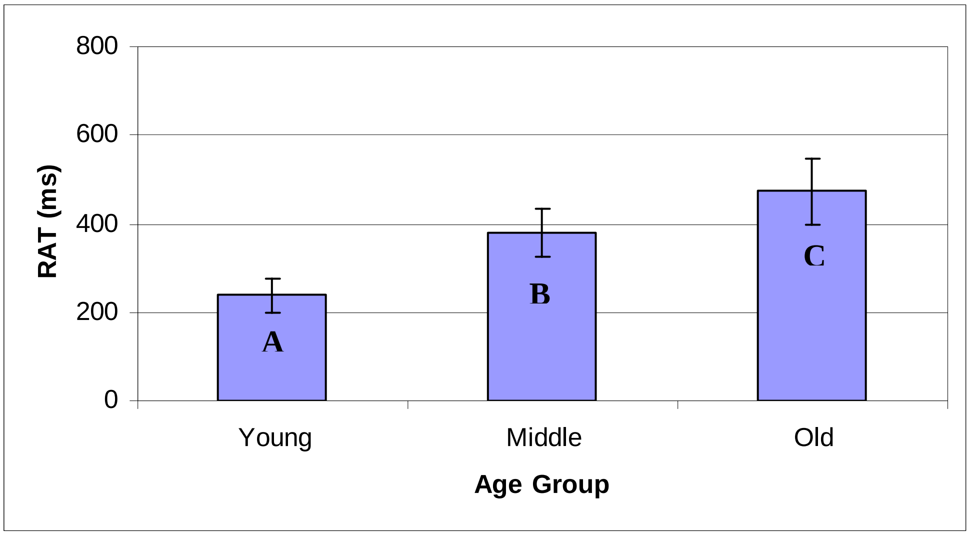


Figure 31: Means and SDs of RAT across the three age groups (Different letters signify significant differences at the $p < 0.05$ level, see Table 14.)

Table 14: Tukey's HSD test of age main effect at alpha=0.05

LSmean – LSmean	Diff	Lower CL Diff	Upper CL Diff	Pr > |t|
Younger – Middle-aged	-142.694	-152.253	-133.134	**<.0001**
Younger – Older	-234.439	-243.998	-224.879	**<.0001**
Middle-aged – Older	-91.745	-101.305	-82.186	**<.0001**

b) Light intensity main effect

In general, reaction times were significantly different under the two light intensity levels ($F_{(2,26)}$=57.91, P<.0001), and light of lower intensity resulted in a longer reaction time (Table 15, Figure 32).

Table 15: Descriptive statistics of light intensity main effect on RAT

Light Intensity	RAT Mean (ms)	Standard Deviation
Bright (100 cd/m^2)	332.938	93.284
Dark (20 cd/m^2)	394.976	121.239

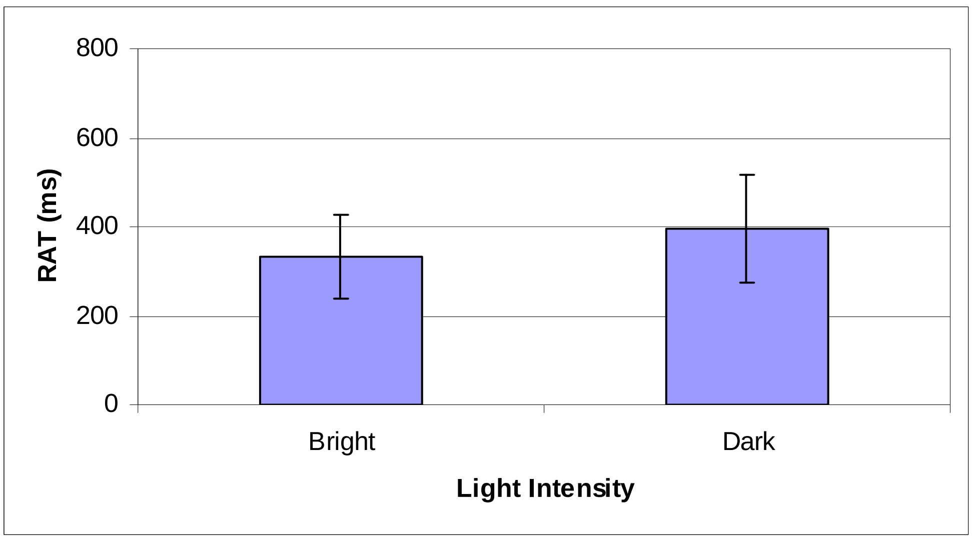


Figure 32: Means and SDs of RAT for the two light intensity levels

c) Light chromaticity main effect

Under the two light chromaticity levels, reaction times were significantly different from each other ($F_{(2,26)}$=9.62, P=0.0007). Compared with the blue image, the participants spent less time to start to accommodate the red image (Table 16, Figure 33).

Table 16: Descriptive statistics of light chromaticity main effect on RAT

Light Chromaticity	RAT Mean (ms)	Standard Deviation
Blue	376.760	109.769
Red	351.155	113.850

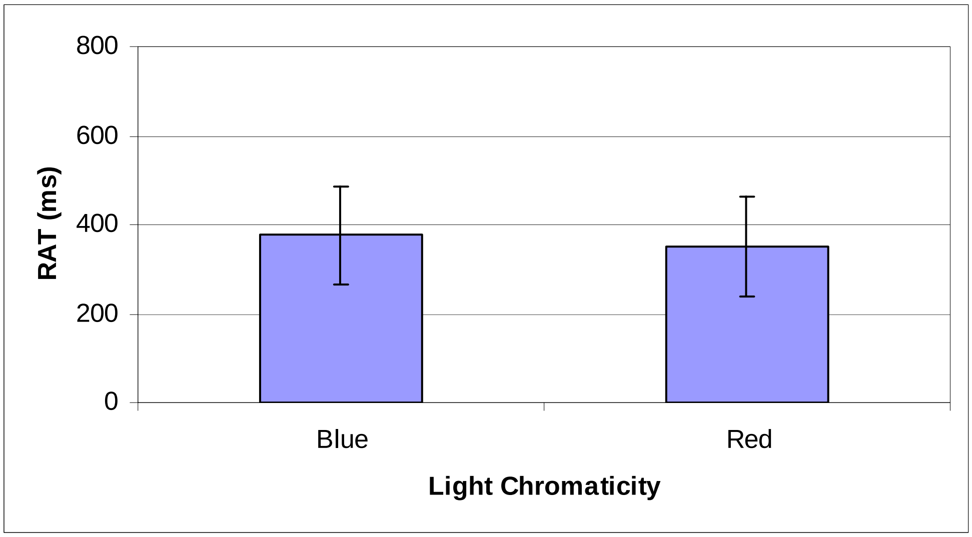


Figure 33: Means and SDs of RAT for the two light chromaticity levels

4.2.2.2 The interaction effects

a) Age x light intensity effect

The interaction between age and light intensity was found to be statistically significant ($F_{(4,52)}=8.17$, $P<.0001$). Table 17 and Figure 34 indicate that the participants from each of the age groups spent a longer time to react to the stimulus when the image was dark.

Table 17: Descriptive statistics of age x light intensity effect on RAT

Interaction	RAT Mean (ms)	Standard Deviation
Younger, Bright	224.189	30.863
Younger, Dark	252.305	38.252
Middle-aged, Bright	350.646	40.170
Middle-aged, Dark	411.235	48.038
Older, Bright	423.981	55.075
Older, Dark	521.390	59.510

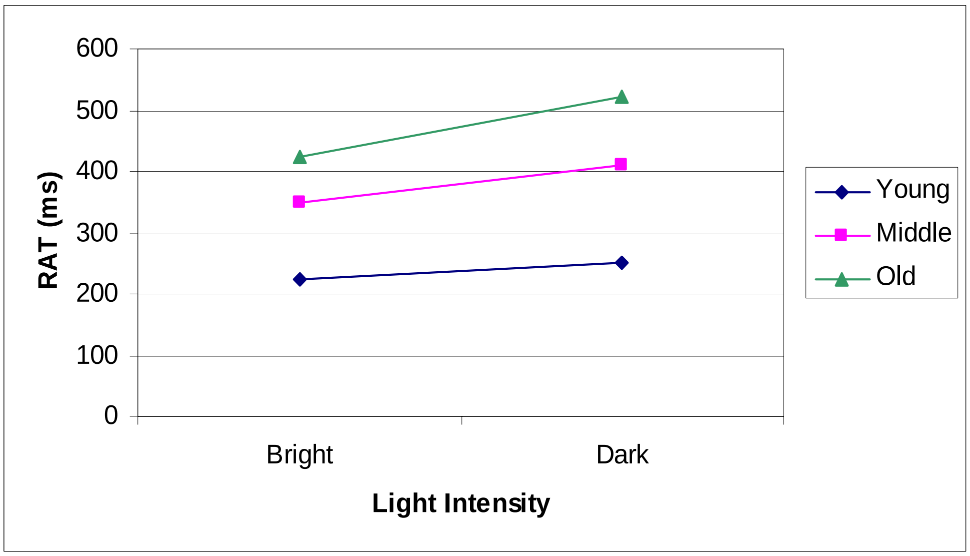


Figure 34: Age x light intensity on RAT

b) Age x light chromaticity effect

The interaction between age and light chromaticity was not statistically significant ($F_{(4,52)}$=1.34, P=0.2674, Figure 35).

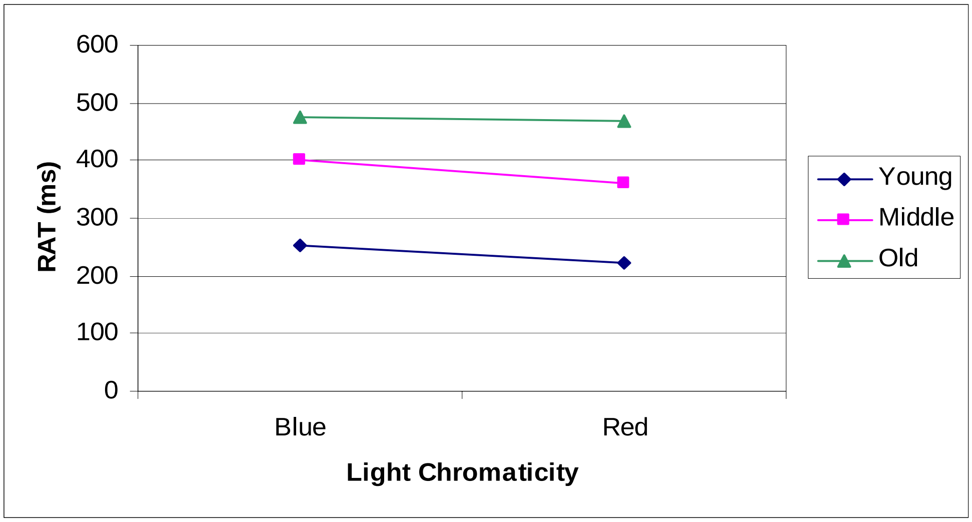


Figure 35: Age x light chromaticity on RAT

c) Light intensity x light chromaticity effect

No statistically significant interaction effect was found between light intensity and light chromaticity ($F_{(2,26)}$=0.81, P=0.4554, Figure 36).

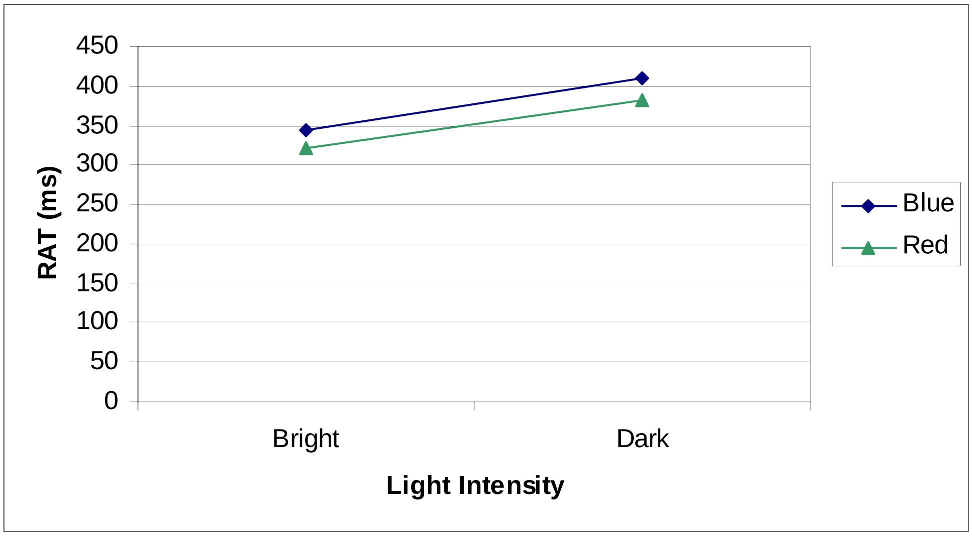


Figure 36: Light intensity x light chromaticity on RAT

4.2.2.3 Summary of the ANOVA test on RAT

In summary, the accommodative performance, in terms of RAT, declined with aging, decreased light intensity, and bluish light chromaticity. The results indicated that the older participants had the longest reaction time, and also had the largest increase of reaction time when the intensity of light was reduced from 100 cd/m^2 to 20 cd/m^2.

4.2.3 The univariate ANOVA test for the response time index (RTI)

The results of the univariate ANOVA test for the response time index are summarized in Table 18. The response time index is defined as the division of the time between the onset and offset of accommodation by the actual accommodative distance (Figure 5). In general, the effects of age group, light intensity, and light chromaticity were all statistically significant. The interaction effects between age group and light intensity and between light intensity and light chromaticity were also of statistical significance.

Table 18: ANOVA test for the response time index

Source	**Error**	**F Value**	**Prob > F**
Age	Subject(Age)	$F_{(4,52)}$=3.10	**0.0230**
Intensity	Intensity*Subject(Age)	$F_{(2,26)}$=53.43	**<.0001**
Color	Color*Subject(Age)	$F_{(2,26)}$=29.53	**<.0001**
Age*Intensity	Intensity*Subject(Age)	$F_{(4,52)}$=8.74	**<.0001**
Age*Color	Color*Subject(Age)	$F_{(4,52)}$=5.36	**0.0011**
Intensity*Color	Intensity*Color* Subject(Age)	$F_{(2,26)}$=2.13	0.1394
Age*Intensity*Color	Intensity*Color* Subject(Age)	$F_{(4,52)}$=1.72	0.1594

4.2.3.1 The main effects

a) Age group main effect

Overall, aging led to an increase of the response time index. The differences were statistically significant ($F_{(4,52)}$=3.10, P=0.0230). The means and standard deviations of the response time index for the three age groups are listed in Table 19 and illustrated in Figure 37. A Tukey post-hoc test indicated that the response time indices were different across the three age groups (Table 20).

Table 19: Descriptive statistics of age main effect on RTI

Age Group	RTI Mean (ms/m)	Standard Deviation
Younger	343.751	47.473
Middle-aged	388.720	49.985
Older	440.858	98.133

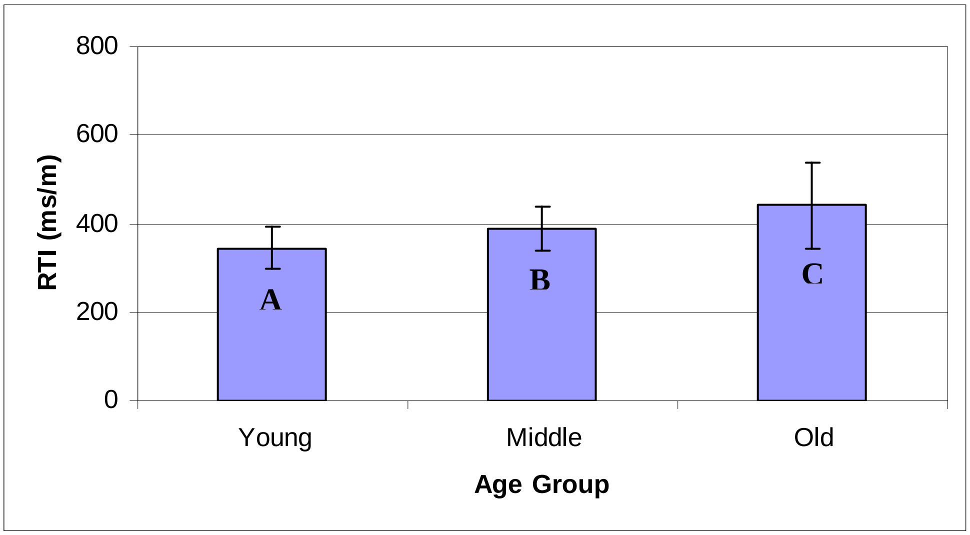


Figure 37: Means and SDs of RTI across the three age groups (Different letters signify significant differences at the $p < 0.05$ level, see Table 20.)

Table 20: Tukey's HSD test of age main effect at alpha=0.05

LSmean – LSmean	Diff	Lower CL Diff	Upper CL Diff	Pr > |t|
Younger – Middle-aged	-44.969	-52.472	-37.466	**<.0001**
Younger – Older	-97.107	-104.610	-89.604	**<.0001**
Middle-aged – Older	-52.138	-59.641	-44.635	**<.0001**

b) Light intensity main effect

In general, the response time indices were statistically significant under the two light intensity levels ($F_{(2,26)}$=53.43, P<.0001), and light of lower intensity resulted in a larger response time index (Table 21, Figure 38).

Table 21: Descriptive statistics of light intensity main effect on RTI

Light Intensity	RTI Mean (ms/m)	Standard Deviation
Bright (100 cd/m^2)	371.076	85.193
Dark (20 cd/m^2)	411.144	68.234

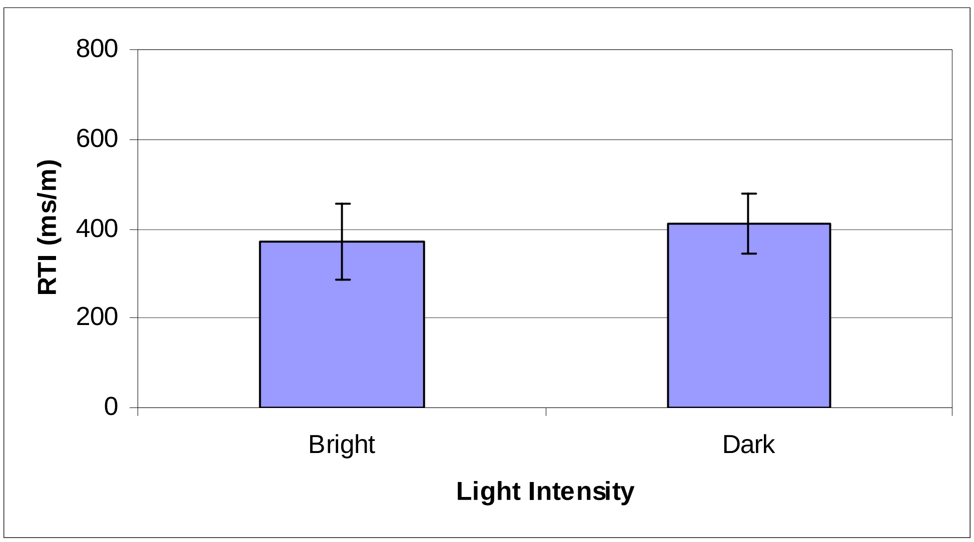


Figure 38: Means and SDs of RTI for the two light intensity levels

c) Light chromaticity main effect

Under the two light chromaticity levels, the response time indices were statistically different ($F_{(2,26)}$=29.53, P<.0001). The participants had a smaller response time index when viewing the red image than when viewing the blue one (Table 22, Figure 39).

Table 22: Descriptive statistics of light chromaticity main effect on RTI

Light Chromaticity	RTI Mean (ms/m)	Standard Deviation
Blue	409.370	66.166
Red	372.850	87.595

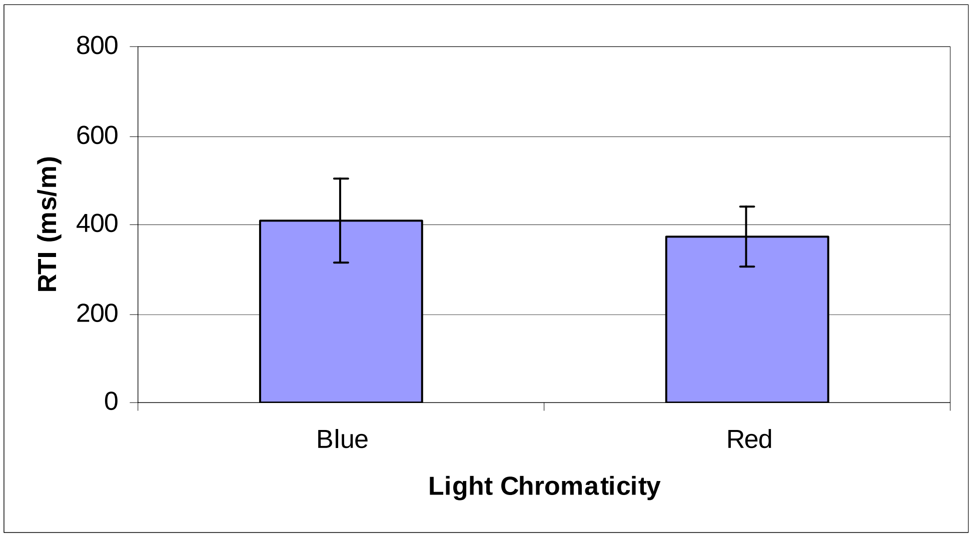


Figure 39: Means and SDs of RTI for the two light chromaticity levels

4.2.3.2 The interaction effects

a) Age x light intensity effect

The interaction between age and light intensity was found to be statistically significant ($F_{(4,52)}$=8.74, P<.0001). The response time index increased for the three groups with the decrease of light intensity (Table 23, Figure 40). However, the older group had the least increase of the response time index.

Table 23: Descriptive statistics of age x light intensity effect on RTI

Interaction	RTI Mean (ms/m)	Standard Deviation
Younger, Bright	318.253	41.288
Younger, Dark	369.249	39.076
Middle-aged, Bright	356.143	34.482
Middle-aged, Dark	421.297	41.171
Older, Bright	438.831	107.020
Older, Dark	442.885	89.695

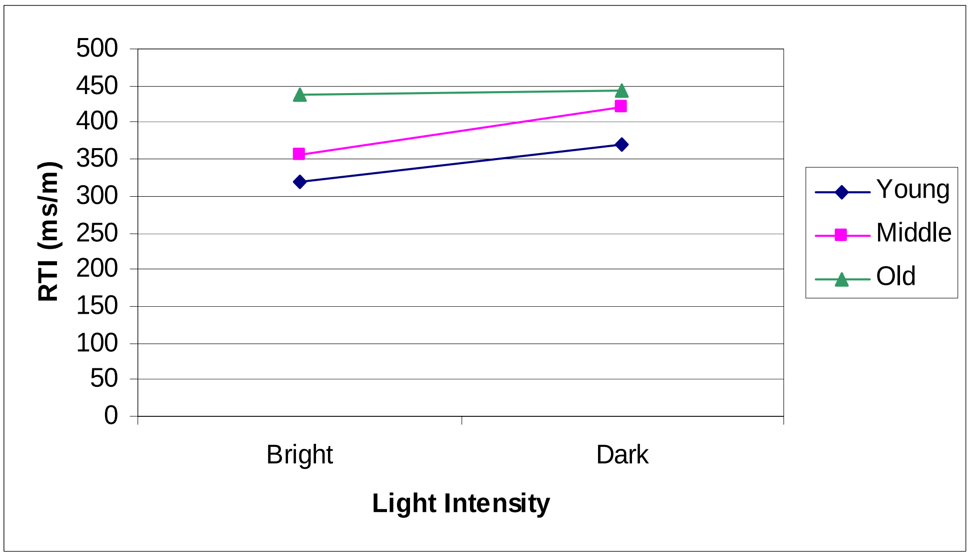


Figure 40: Age x light intensity on RTI

b) Age x light chromaticity effect

The interaction between age and light chromaticity was found to be statistically significant ($F_{(4,52)}$=5.36, P=0.0011). The response time index increased for all of the three age groups when the image was switched from red to blue (Table 24, Figure 41). Nevertheless, the older group had the least change of the response time index.

Table 24: Descriptive statistics of age x light chromaticity effect on RTI

Interaction	RTI Mean (ms/m)	Standard Deviation
Younger, Blue	373.783	34.109
Younger, Red	313.720	39.393
Middle-aged, Blue	408.476	46.935
Middle-aged, Red	368.965	45.360
Older, Blue	445.852	85.599
Older, Red	435.864	110.130

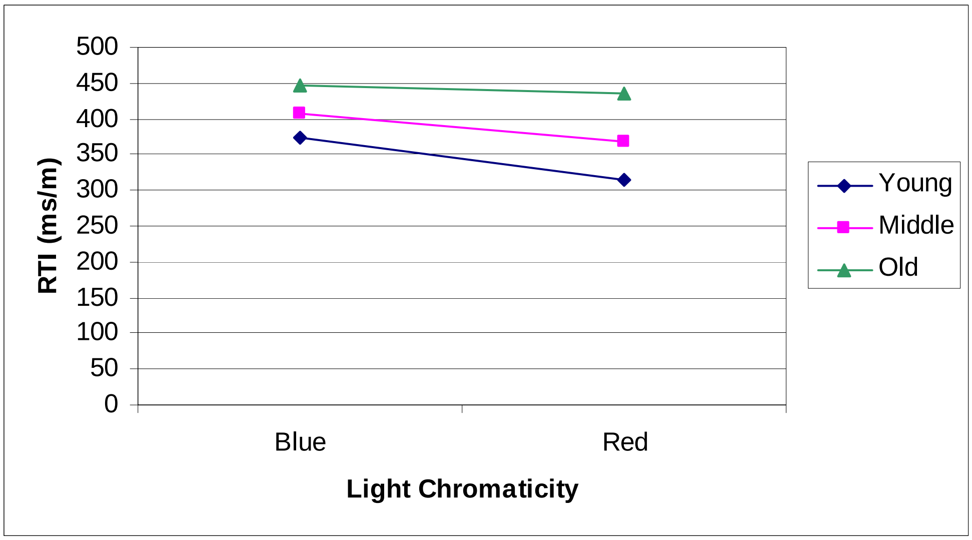


Figure 41: Age x light chromaticity on RTI

c) Light intensity x light chromaticity effect

The interaction between light intensity and light chromaticity was not statistically significant ($F_{(2,26)}$=2.13, P=0.1394, Figure 42).

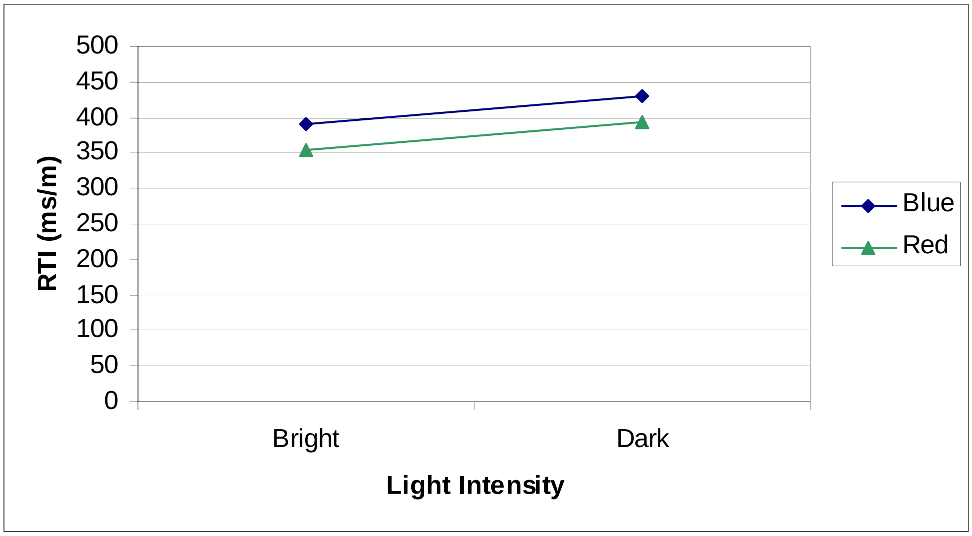


Figure 42: Light intensity x light chromaticity on RTI

4.2.3.3 Summary of the ANOVA test on RTI

In summary, aging, decreased light intensity, and bluish light chromaticity all resulted in the deterioration of the accommodative performance (i.e., the increase of the response time index). For the older participants, their response time indices did not change as much as those of the younger and middle-aged counterparts.

4.2.4 The univariate ANOVA test for the accommodation time index (ATI)

The results of the univariate ANOVA test for the accommodation time index are summarized in Table 25. The accommodation time index is defined as the division of the time between the trigger of the stimulus and the offset of accommodation by the actual accommodative distance (Figure 5). In general, different age groups, light intensities, and light chromaticities all resulted in statistically significant changes of the accommodation time index. Additionally, statistically significant interaction effects were found between age group and light intensity and between age group and light chromaticity.

Table 25: ANOVA test for the accommodation time index

Source	Error	F Value	Prob > F
Age	Subject(Age)	$F_{(4,52)}$=7.51	**<.0001**
Intensity	Intensity*Subject(Age)	$F_{(2,26)}$=447.43	**<.0001**
Color	Color*Subject(Age)	$F_{(2,26)}$=99.83	**<.0001**
Age*Intensity	Intensity*Subject(Age)	$F_{(4,52)}$=7.80	**<.0001**
Age*Color	Color*Subject(Age)	$F_{(4,52)}$=11.22	**<.0001**
Intensity*Color	Intensity*Color* Subject(Age)	$F_{(2,26)}$=2.51	0.1008
Age*Intensity*Color	Intensity*Color* Subject(Age)	$F_{(4,52)}$=1.12	0.3591

4.2.4.1 The main effects

a) Age group main effect

The ANOVA test indicated that aging led to the change of the accommodation time index. The differences were statistically significant ($F_{(4,52)}$=7.51, P<.0001). The means and standard deviations of the accommodation time index for the three age groups are shown in Table 26 and illustrated in Figure 43. A Tukey post-hoc test indicated that the accommodation time indices were different across the age groups (Table 27).

Table 26: Descriptive statistics of age main effect on ATI

Age Group	ATI Mean (ms/m)	Standard Deviation
Younger	415.947	55.049
Middle-aged	504.156	62.320
Older	661.600	147.566

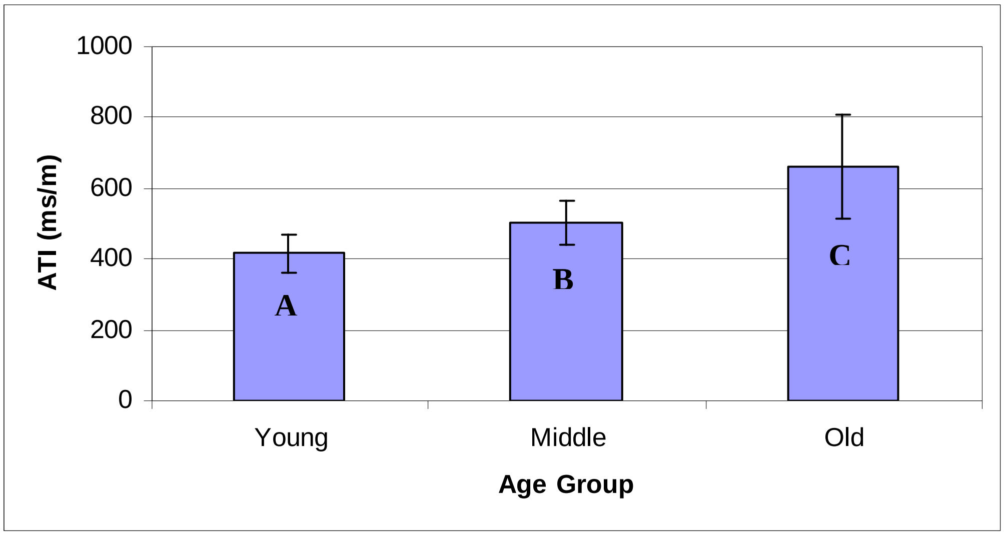


Figure 43: Means and SDs of ATI across the three age groups (Different letters signify significant differences at the $p < 0.05$ level, see Table 27.)

Table 27: Tukey's HSD test of age main effect at alpha=0.05

LSmean – LSmean	Diff	Lower CL Diff	Upper CL Diff	Pr > |t|
Younger – Middle-aged	-88.209	-97.524	-78.894	**<.0001**
Younger – Older	-245.653	-254.968	-236.338	**<.0001**
Middle-aged – Older	-157.444	-166.759	-148.129	**<.0001**

b) Light intensity main effect

In general, the accommodation time indices were statistically different under the two light intensity levels ($F_{(2,26)}=447.43$, $P<.0001$), and light of lower intensity resulted in a larger accommodation time index (Table 28, Figure 44).

Table 28: Descriptive statistics of light intensity main effect on ATI

Light Intensity	ATI Mean (ms/m)	Standard Deviation
Bright (100 cd/m^2)	494.957	138.837
Dark (20 cd/m^2)	559.512	135.980

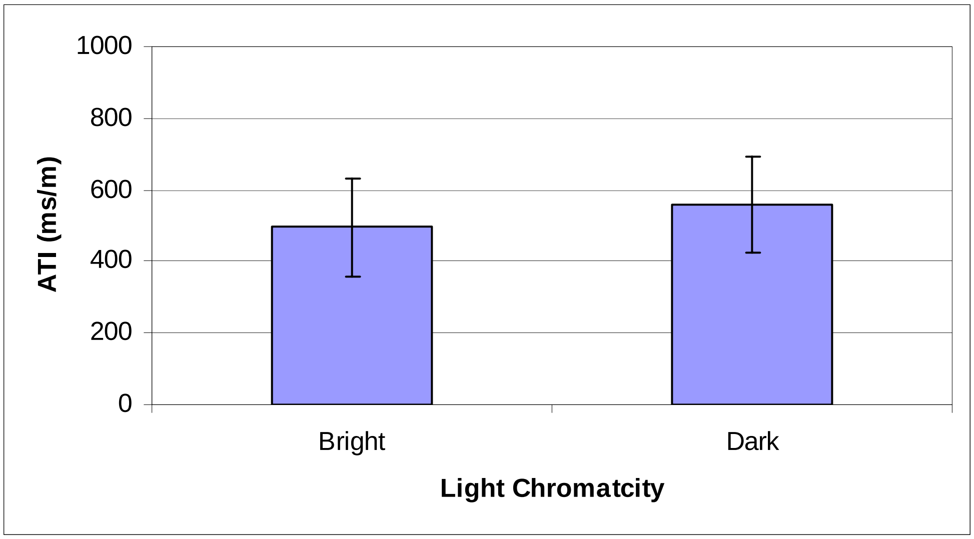


Figure 44: Means and SDs of ATI for the two light intensity levels

c) Light chromaticity main effect

Under the two light chromaticity levels, the accommodation time indices were significantly different ($F_{(2,26)}$=99.83, P<.0001). Compared with the blue image, the participants had a smaller accommodation time index when viewing the red image (Table 29, Figure 45).

Table 29: Descriptive statistics of light chromaticity main effect on ATI

Light Chromaticity	ATI Mean (ms/m)	Standard Deviation
Blue	549.799	128.832
Red	504.669	149.140

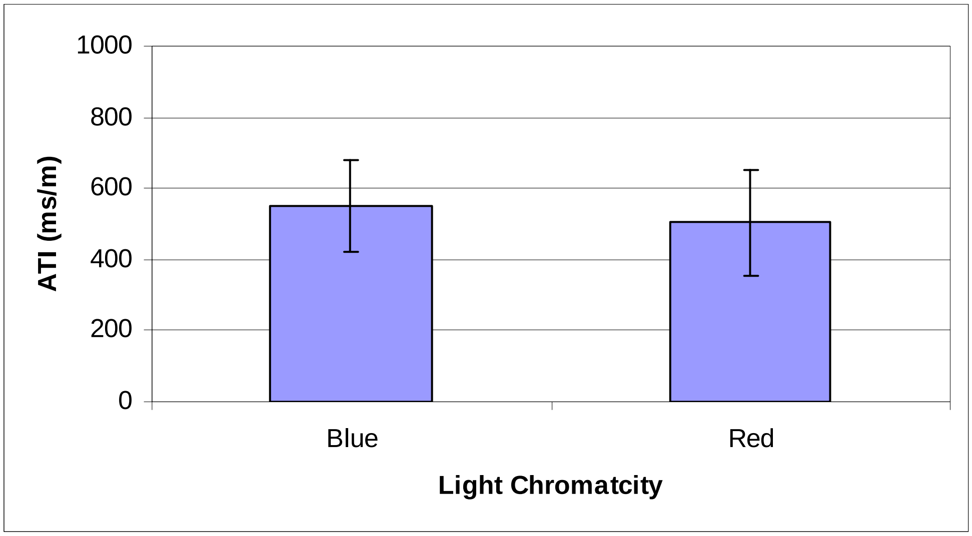


Figure 45: Means and SDs of ATI for the two light chromaticity levels

4.2.4.2 The interaction effects

a) Age x light intensity effect

The interaction between age and light intensity was found to be statistically significant ($F_{(4,52)}$=7.80, P<.0001). The accommodation time index changed for the three age groups under different light intensities (Table 30, Figure 46).

Table 30: Descriptive statistics of age x light intensity effect on ATI

Interaction	ATI Mean (ms/m)	Standard Deviation
Younger, Bright	386.189	46.913
Younger, Dark	445.705	46.057
Middle-aged, Bright	462.399	41.002
Middle-aged, Dark	545.913	51.081
Older, Bright	636.282	145.698
Older, Dark	686.918	146.856

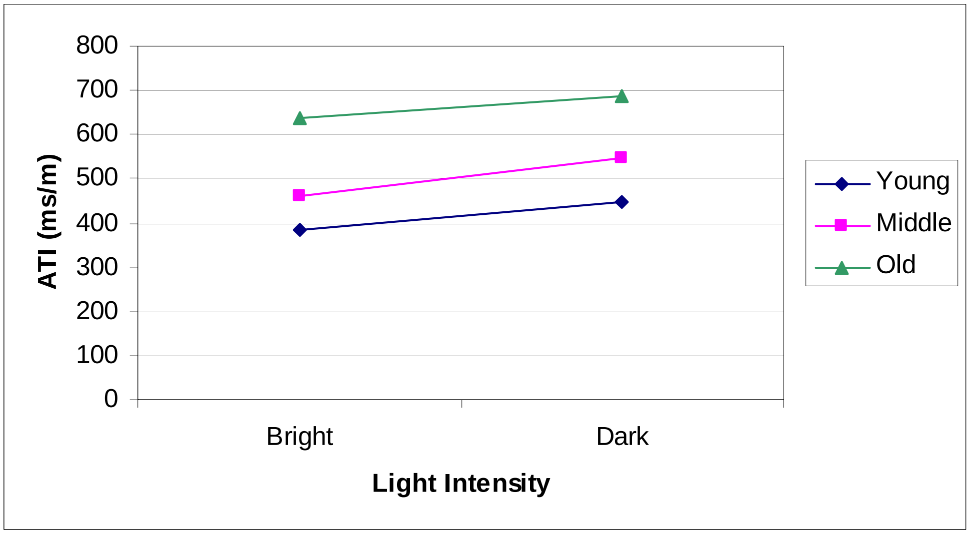


Figure 46: Age x light intensity on ATI

b) Age x light chromaticity effect

The interaction effect between age and light chromaticity was found to be statistically significant ($F_{(4,52)}$=11.22, P<.0001). The accommodation time index increased for the three age groups when the near target was switched from red to blue (Table 31, Figure 47).

Table 31: Descriptive statistics of age x light chromaticity effect on ATI

Interaction	ATI Mean (ms/m)	Standard Deviation
Younger, Blue	450.646	42.620
Younger, Red	381.249	43.040
Middle-aged, Blue	529.645	57.936
Middle-aged, Red	478.668	56.374
Older, Blue	669.108	142.728
Older, Red	654.092	153.696

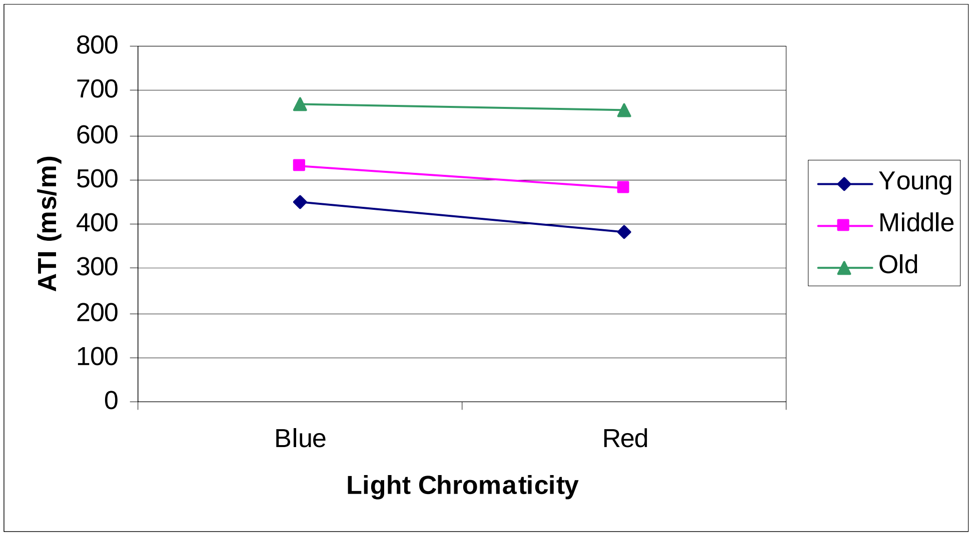


Figure 47: Age x light chromaticity on ATI

c) Light intensity x light chromaticity effect

No statistically significant interaction effect was found between light intensity and light chromaticity ($F_{(2,26)}$=2.51, P=0.1008, Figure 48).

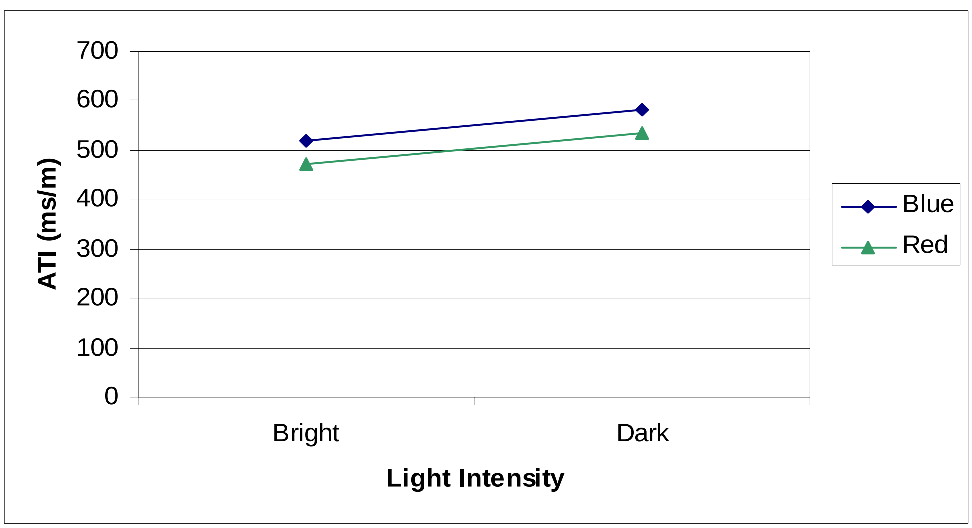


Figure 48: Light intensity x light chromaticity on ATI

4.2.4.3 Summary of the ANOVA test on ATI

To summarize, aging, decreased light intensity, and bluish light chromaticity all led to an increase of the accommodation time index.

4.2.5 The univariate ANOVA test for the peak velocity (PV)

The results of the univariate ANOVA test for the peak velocity are summarized in Table 32. The peak velocity is defined as the maximum velocity of accommodation during the response time (Figure 5). In general, different age groups, light intensities, and light chromaticities all led to statistically significant changes of the peak velocity. Additionally, all of the two-way interaction effects were statistically significant.

Table 32: ANOVA test for the peak velocity

Source	**Error**	**F Value**	**Prob > F**
Age	Subject(Age)	$F_{(4,52)}$=9.06	**<.0001**
Intensity	Intensity*Subject(Age)	$F_{(2,26)}$=49.83	**<.0001**
Color	Color*Subject(Age)	$F_{(2,26)}$=43.07	**<.0001**
Age*Intensity	Intensity*Subject(Age)	$F_{(4,52)}$=3.95	**0.0071**
Age*Color	Color*Subject(Age)	$F_{(4,52)}$=5.88	**0.0006**
Intensity*Color	Intensity*Color* Subject(Age)	$F_{(2,26)}$=13.42	**<.0001**
Age*Intensity*Color	Intensity*Color* Subject(Age)	$F_{(4,52)}$=1.73	0.1580

4.2.5.1 The main effects

a) Age group main effect

Overall, aging led to a decrease of the peak velocity. The differences were statistically significant ($F_{(4,52)}$=9.06, P<.0001). The means and standard deviations of the peak velocity for the three age groups are listed in Table 33 and illustrated in Figure 49. A Tukey's HSD test indicated that the peak velocities were significantly different across the three age groups (Table 34).

Table 33: Descriptive statistics of age main effect on PV

Age Group	PV Mean (Diopter/sec)	Standard Deviation
Younger	1.723	0.601
Middle-aged	0.939	0.577
Older	0.462	0.253

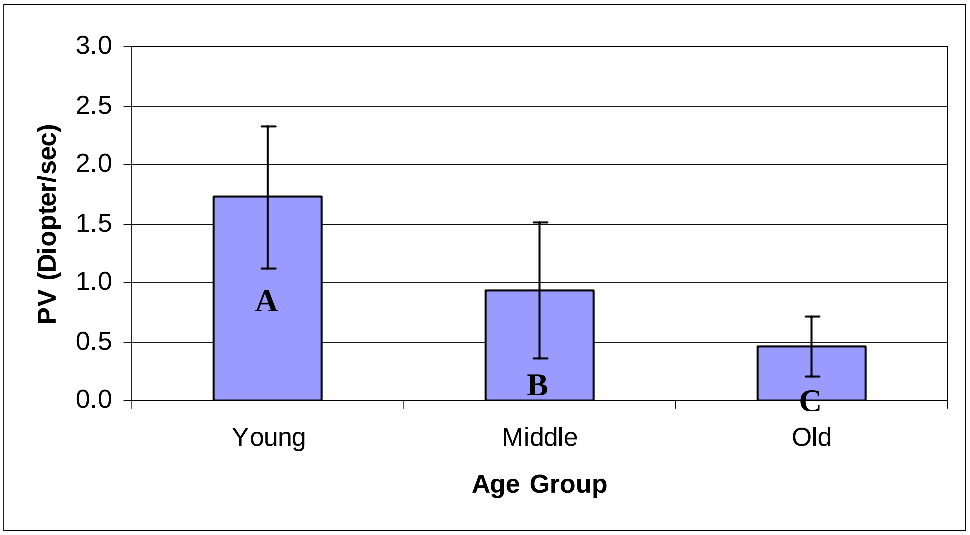


Figure 49: Means and SDs of PV across the three age groups (Different letters signify significant differences at the $p < 0.05$ level, see Table 34.)

Table 34: Tukey's HSD test of age main effect at alpha=0.05

LSmean – LSmean	Diff	Lower CL Diff	Upper CL Diff	Pr > |t|
Younger – Middle-aged	0.784	0.694	0.874	**<.0001**
Younger – Older	1.261	1.171	1.351	**<.0001**
Middle-aged – Older	0.477	0.387	0.566	**<.0001**

b) Light intensity main effect

In general, the peak velocities were significantly different under the two light intensity levels ($F_{(2,26)}$=49.83, P<.0001), and light of higher intensity resulted in a higher peak velocity (Table 35, Figure 50).

Table 35: Descriptive statistics of light intensity main effect on PV

Light Intensity	PV Mean (Diopter/sec)	Standard Deviation
Bright (100 cd/m^2)	1.185	0.770
Dark (20 cd/m^2)	0.898	0.643

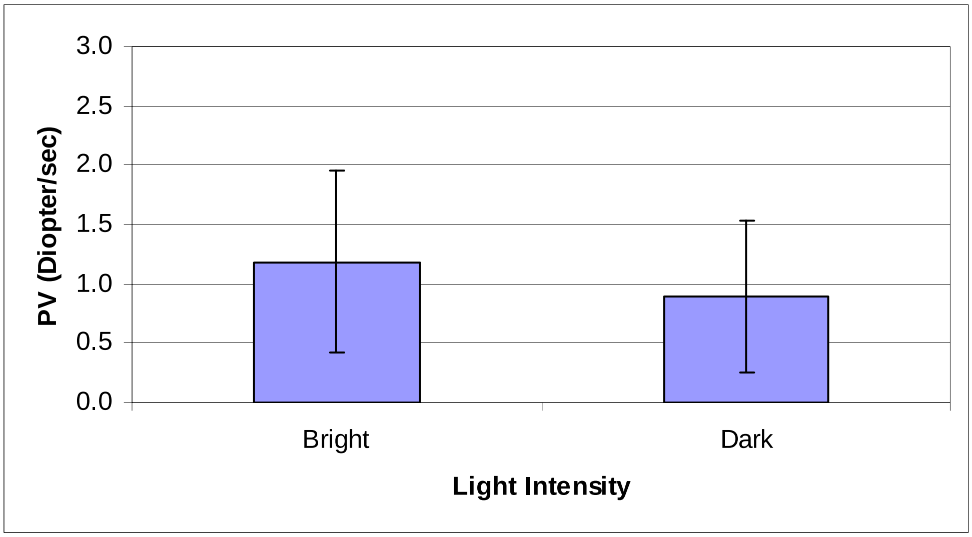


Figure 50: Means and SDs of PV for the two light intensity levels

c) Light chromaticity main effect

Under the two light chromaticity levels, the peak velocities were significantly different ($F_{(2,26)}$=43.07, P<.0001). Compared with the blue image, the participants had a higher peak velocity when viewing the red image (Table 36, Figure 51).

Table 36: Descriptive statistics of light chromaticity main effect on PV

Light Chromaticity	PV Mean (Diopter/sec)	Standard Deviation
Blue	0.913	0.630
Red	1.170	0.786

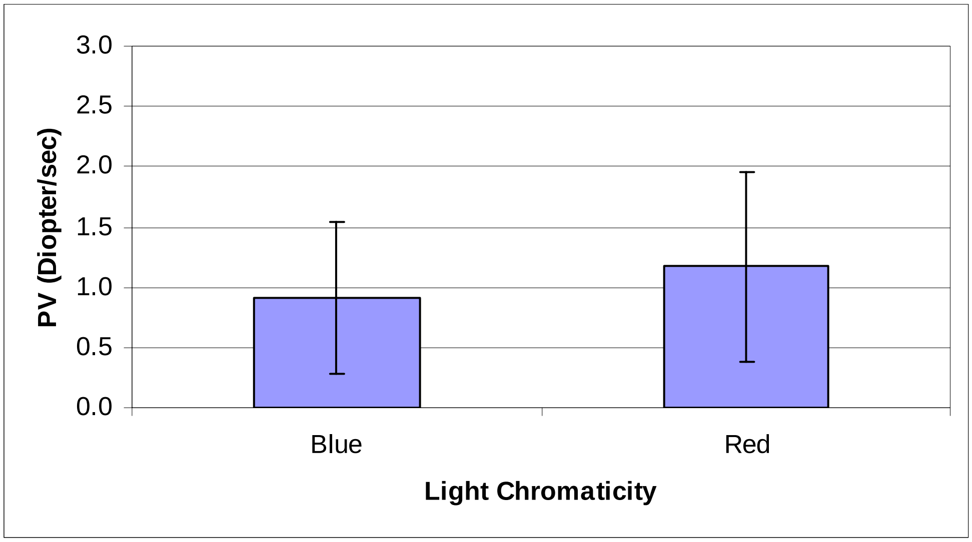


Figure 51: Means and SDs of PV for the two light chromaticity levels

4.2.5.2 The interaction effects

a) Age x light intensity effect

The interaction between age and light intensity was found to be statistically significant ($F_{(4,52)}$=3.95, P=0.0071). The peak velocity declined for the three age groups with the decrease of light intensity (Table 37, Figure 52).

Table 37: Descriptive statistics of age x light intensity effect on PV

Interaction	PV Mean (Diopter/sec)	Standard Deviation
Younger, Bright	1.879	0.624
Younger, Dark	1.568	0.540
Middle-aged, Bright	1.126	0.658
Middle-aged, Dark	0.752	0.412
Older, Bright	0.550	0.273
Older, Dark	0.375	0.198

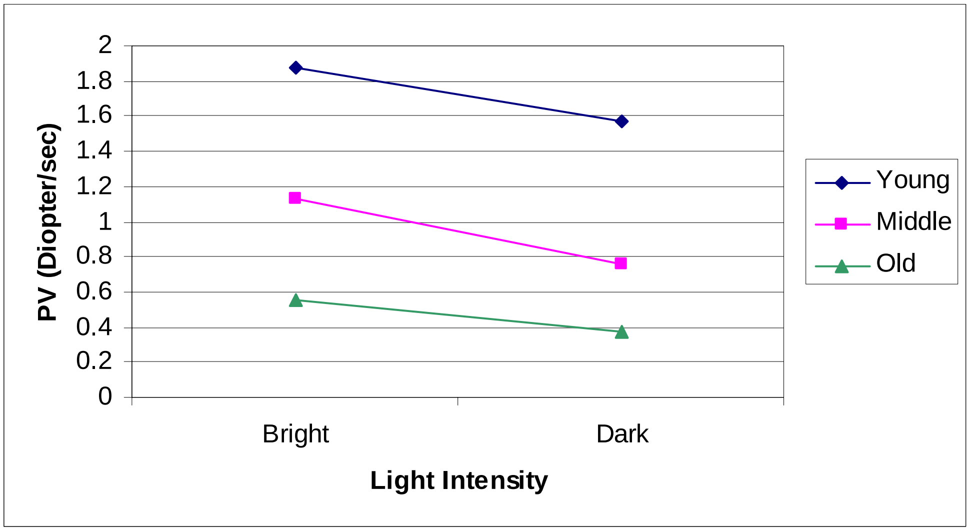


Figure 52: Age x light intensity on PV

b) Age x light chromaticity effect

The interaction between age and light chromaticity was found to be statistically significant ($F_{(4,52)}$=5.88, P=0.0006). In terms of the peak velocity, all of the participants accommodated the red image faster than the blue one (Table 38, Figure 53).

Table 38: Descriptive statistics of age x light chromaticity effect on PV

Interaction	PV Mean (Diopter/sec)	Standard Deviation
Younger, Blue	1.578	0.468
Younger, Red	1.868	0.685
Middle-aged, Blue	0.739	0.446
Middle-aged, Red	1.139	0.628
Older, Blue	0.421	0.245
Older, Red	0.504	0.256

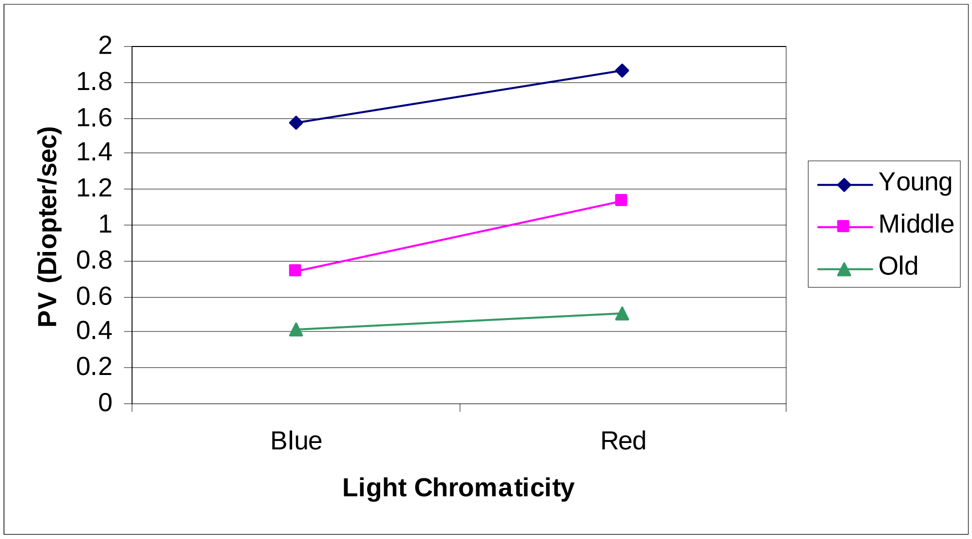


Figure 53: Age x light chromaticity on PV

c) Light intensity x light chromaticity effect

The interaction between light intensity and light chromaticity was statistically significant ($F_{(2,26)}$=13.42, P<.0001, Table 39, Figure 54).

Table 39: Descriptive statistics of light intensity x light chromaticity effect on PV

Interaction	PV Mean (Diopter/sec)	Standard Deviation
Bright, Blue	0.989	0.670
Bright, Red	1.381	0.817
Dark, Blue	0.837	0.582
Dark, Red	0.959	0.699

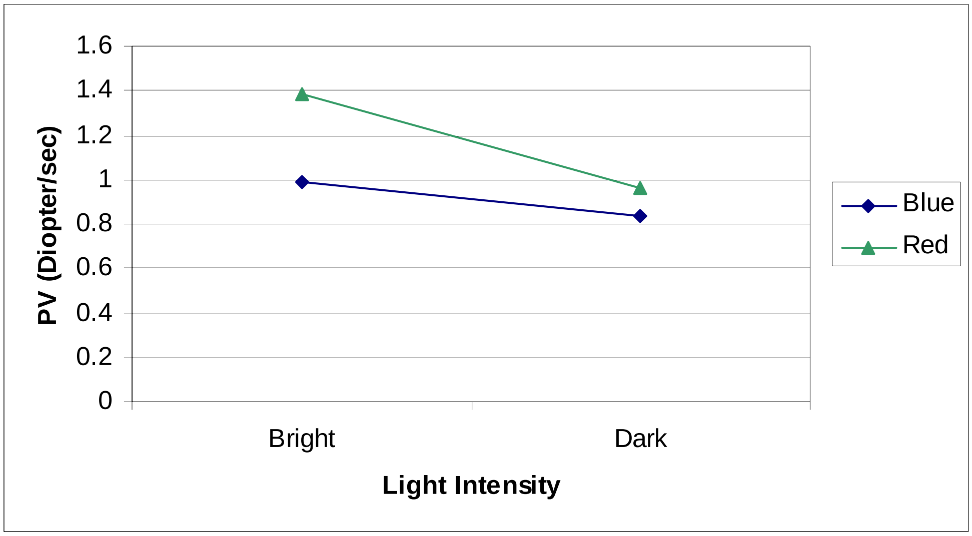


Figure 54: Light intensity x light chromaticity on PV

4.2.5.3 Summary of the ANOVA test on PV

In summary, aging, decreased light intensity, and bluish light chromaticity all reduced the peak velocity.

4.2.6 The univariate ANOVA test for the percentage of time to reach its peak (Time%)

The last dependent variable is the percentage of time it takes the velocity to reach its peak. The results of the univariate ANOVA test for Time% are summarized in Table 40. In general, different age groups, light intensities, and light chromaticities all led to statistically significant changes of the percentage of time for the velocity to reach its peak. On the other hand, none of the interaction effects was found to be statistically significant.

Table 40: ANOVA test for Time%

Source	**Error**	**F Value**	**Prob > F**
Age	Subject(Age)	$F_{(4,52)}$=7.82	**<.0001**
Intensity	Intensity*Subject(Age)	$F_{(2,26)}$=67.92	**<.0001**
Color	Color*Subject(Age)	$F_{(2,26)}$=93.84	**<.0001**
Age*Intensity	Intensity*Subject(Age)	$F_{(4,52)}$=1.55	0.2024
Age*Color	Color*Subject(Age)	$F_{(4,52)}$=1.59	0.1933
Intensity*Color	Intensity*Color* Subject(Age)	$F_{(2,26)}$=1.54	0.2340
Age*Intensity*Color	Intensity*Color* Subject(Age)	$F_{(4,52)}$=2.08	0.0973

4.2.6.1 The main effects

a) Age group main effect

Overall, aging led to a decrease of the percentage of time for the velocity to reach its peak. The differences were statistically significant ($F_{(4,52)}$=7.82, P<.0001). The means and standard deviations of Time% for the three age groups are listed in Table 41 and illustrated in Figure 55. A Tukey post-hoc test indicated that Time% was different across the three age groups (Table 42).

Table 41: Descriptive statistics of age main effect on Time%

Age Group	Time%	Standard Deviation
Younger	39.807	7.807
Middle-aged	32.954	6.389
Older	27.787	5.852

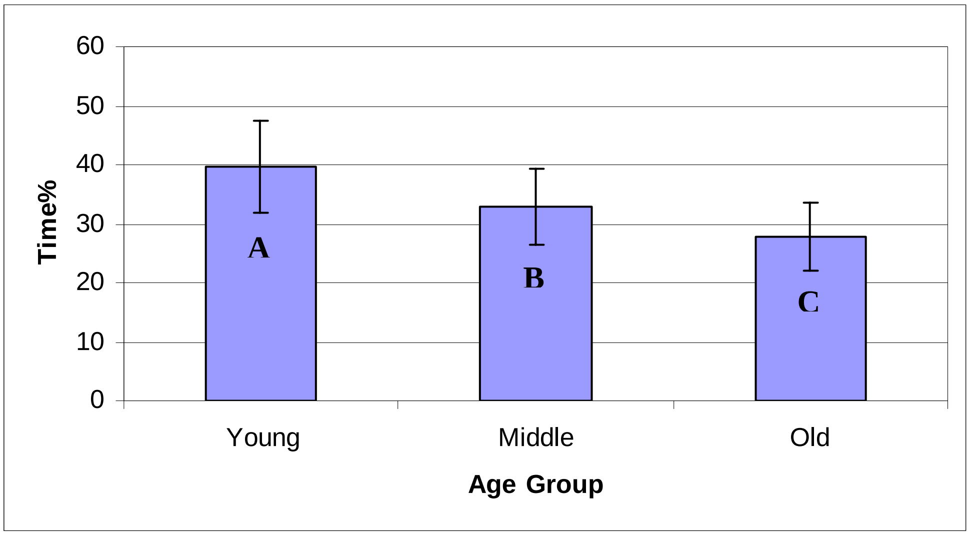


Figure 55: Means and SDs of Time% across the three age groups (Different letters signify significant differences at the $p < 0.05$ level, see Table 42.)

Table 42: Tukey's HSD test of age main effect at alpha=0.05

LSmean – LSmean	Diff	Lower CL Diff	Upper CL Diff	Pr > |t|
Younger – Middle-aged	6.853	5.357	8.348	**<.0001**
Younger – Older	12.020	10.525	13.516	**<.0001**
Middle-aged – Older	5.168	3.672	6.663	**<.0001**

b) Light intensity main effect

In general, the percentages of time to reach the peak velocity were statistically different under the two light intensity levels ($F_{(2,26)}$=67.92, P<.0001), and light of higher intensity resulted in a lower Time% (Table 43, Figure 56).

Table 43: Descriptive statistics of light intensity main effect on Time%

Light Intensity	Time%	Standard Deviation
Bright (100 cd/m^2)	30.237	7.204
Dark (20 cd/m^2)	36.794	8.100

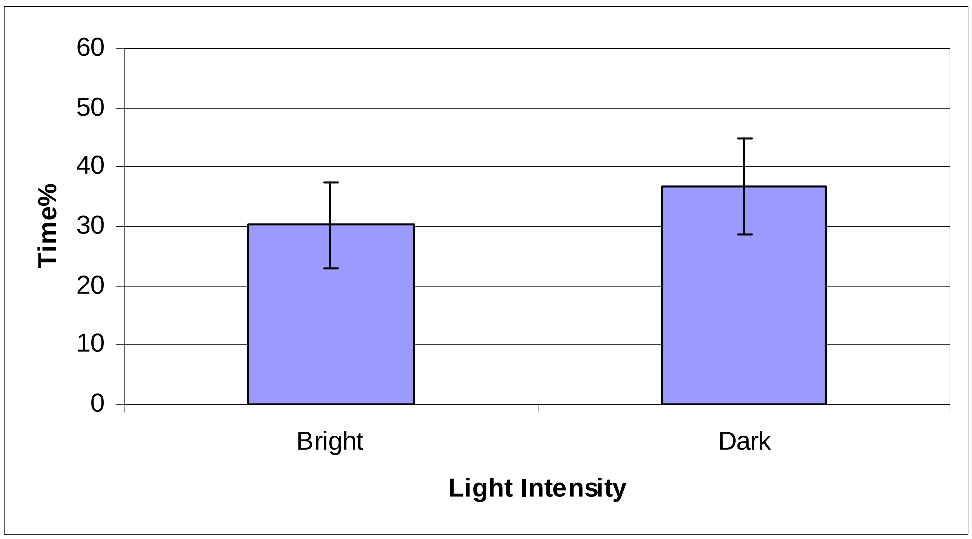


Figure 56: Means and SDs of Time% for the two light intensity levels

c) Light chromaticity main effect

Under the two light chromaticity levels, Time% was significantly different ($F_{(2,26)}$=93.84, P<.0001). The participants had a lower Time% when viewing the red image than when viewing the blue image (Table 44, Figure 57).

Table 44: Descriptive statistics of light chromaticity main effect on Time%

Light Chromaticity	Time%	Standard Deviation
Blue	35.559	8.253
Red	31.472	7.915

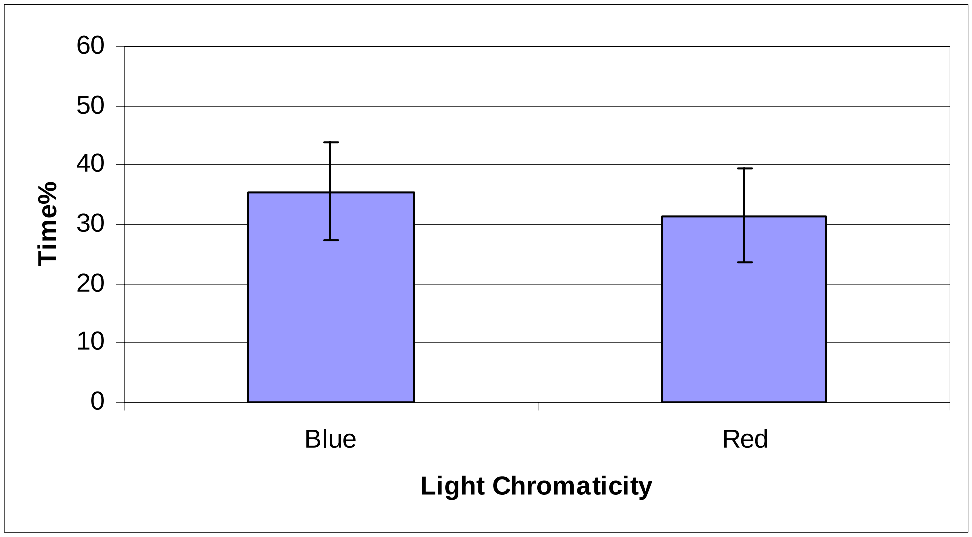


Figure 57: Means and SDs of Time% for the two light chromaticity levels

4.2.6.2 The interaction effects

a) Age x light intensity effect

No statistically significant interaction effect between age and light intensity was found ($F_{(4,52)}$=1.55, P=0.2024, Figure 52).

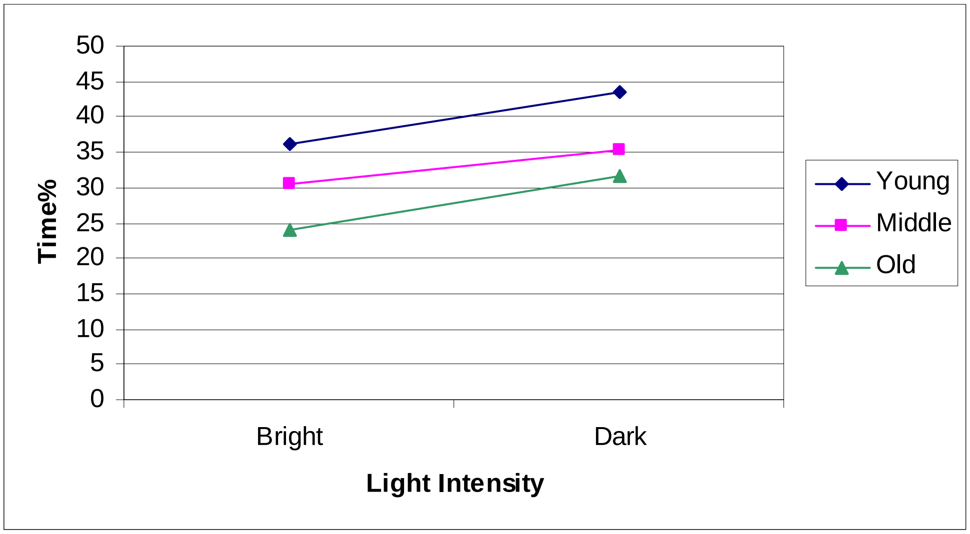


Figure 58: Age x light intensity on Time%

b) Age x light chromaticity effect

The interaction between age and light chromaticity was found to be of no statistical significance ($F_{(4,52)}$=1.59, P=0.1933, Figure 59).

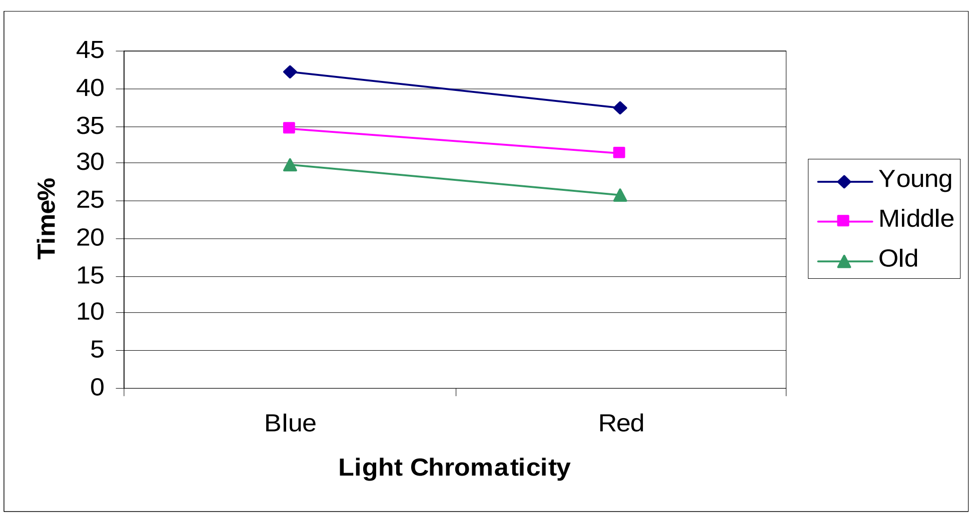


Figure 59: Age x light chromaticity on Time%

c) Light intensity x light chromaticity effect

The interaction between light intensity and light chromaticity was not statistically significant ($F_{(2,26)}$=1.54, P=0.2340, Figure 60).

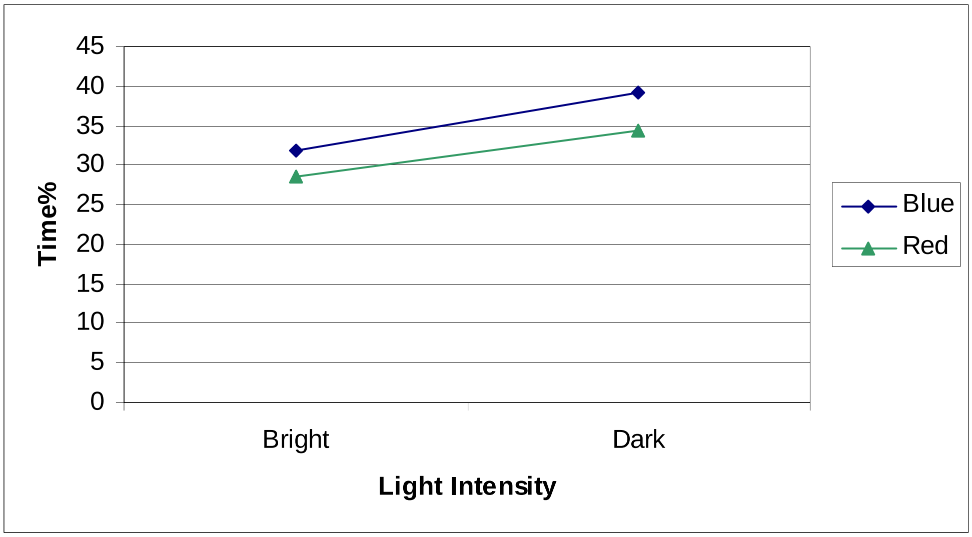


Figure 60: Light intensity x light chromaticity on Time%

4.2.6.3 Summary of the ANOVA test on Time%

In terms of the percentage of time to reach the peak velocity, aging, decreased light intensity, and bluish light chromaticity all led to a change of Time%. No interaction effects among age, light intensity and light chromaticity were statistically significant.

4.2.7 Summary of the results

In summary, the results of the statistical analysis indicated that the age-related changes of the eye, the intensity of light, the chromaticity of light, and their interactions all had statistically significant impacts on dynamic accommodative performance. With the advancing of age, the magnitude of accommodation declined, the participants spent a longer time to react to the stimulus, and the accommodation response became longer and slower. Similar changes were also found when the intensity of light was reduced or the chromaticity of light was switched from red to blue. As for the interaction effects, the effects of aging on most of the dynamic accommodative characteristics were modified by different levels of light intensity or light chromaticity.

4.3 Logistic regression of a typical accommodation response

The current study investigated the dynamic accommodative performance for people at different ages and under different light intensities and chromaticities. Based on the mean values of the smoothed data (Figure 61), a typical accommodation response was obtained within each level of the three independent variables. Logistic regression[9] was therefore applied to model each of the mean responses (Figure 61). The results of the logistic regression can be used to predict the actual focus of the eye at any point of time during an accommodation process that is within the scope of the study.

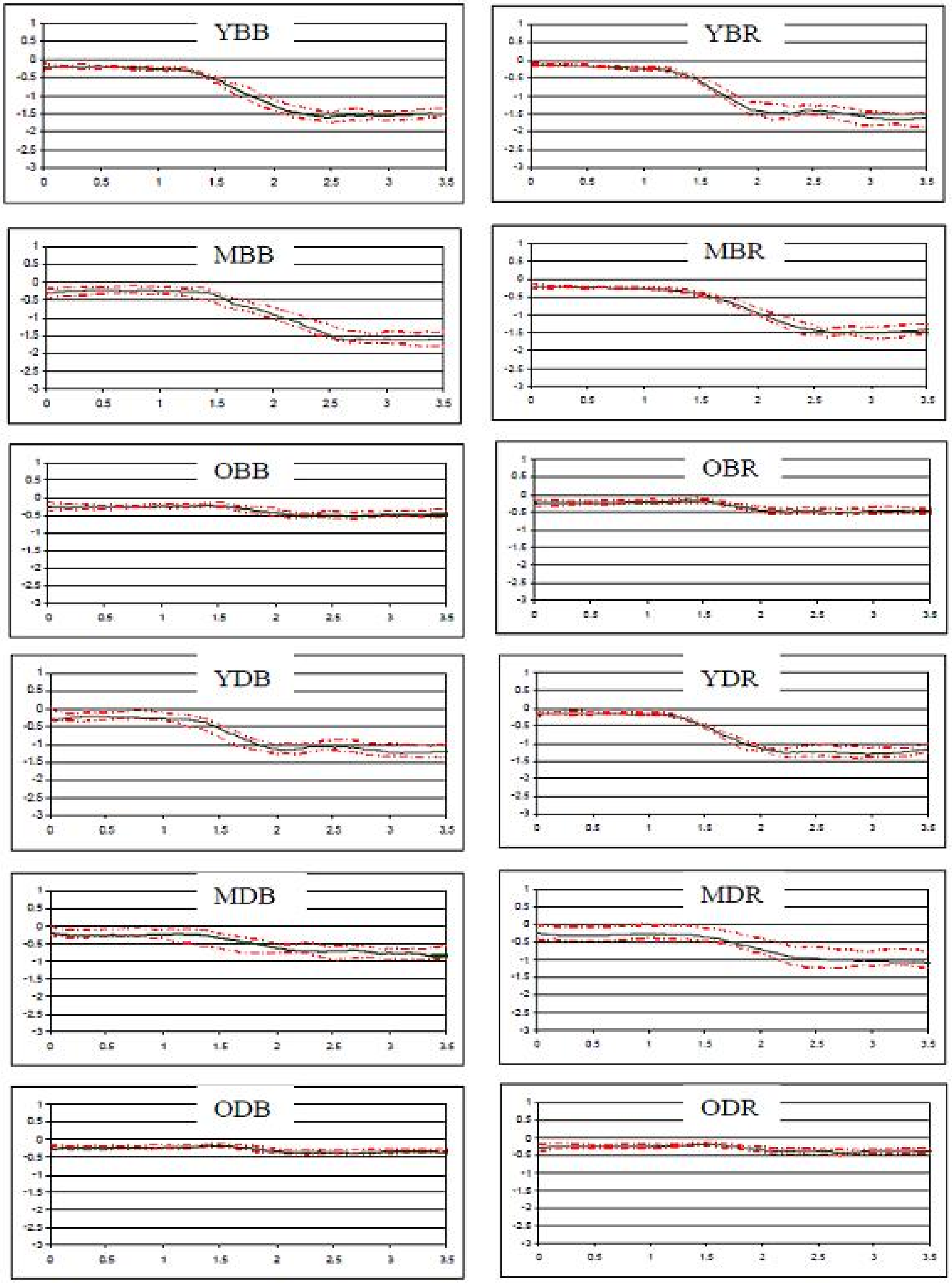
Specifically, an ideal accommodation response under the setup of the current study should have an upper-ceiling value of -0.25 Diopters and a lower-ceiling value of -1.5 Diopters (Figure 62), which is similar to a logistic curve. As a result, a logistic model was used to predict the response:

$$\text{Predicted SE value} = -0.25 - \frac{M}{1+e^{a+b*t}} \qquad \text{(equation 7);}$$

where Parameter a and Parameter b adjust the shape of the logistic curve, and Parameter M controls the lower ceiling value which is determined by the average magnitude of accommodation (e.g., M=1.25 for the younger group under the light intensity level at 100 cd/m^2 and the chromaticity level at blue or red).

As such, Parameter M was first determined based on the accommodation response under a certain combination of age group, light intensity and light chromaticity. Then the measured SE values were imported to the equation to obtain Parameter a and Parameter b.

[9] Logistic regression is a statistical regression model for Bernoulli-distributed dependent variables, that is, y=1/(1+exp(a+bx)).



Y-axis: Spherical Equivalent (Diopter); X-axis: Time (second)

Figure 61: Mean (Black Solid) and Max/Min (Red Dash) curves: Y (Younger), M (Middle-aged), O (Older), Middle B (Bright), D (Dark), Right B(Blue), R (Red)

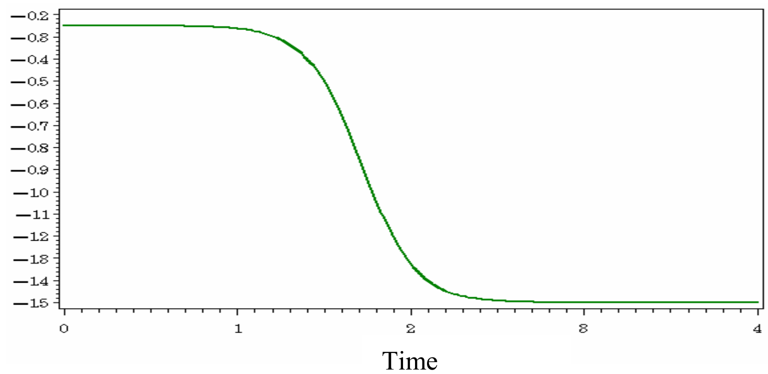


Figure 62: An ideal accommodation response

For example, Figure 63 illustrates the regressed curve and the mean accommodation response for the younger group with the light intensity level and chromaticity level set at Bright and Blue respectively. The logistic regression indicated that the values of Parameter a and Parameter b were statistically different from 0 and the R^2 between the mean values and the predicted ones was > 0.99. The logistic model was

$$\text{Predicted SE value} = -0.25 - \frac{1.25}{1 + e^{10.94 - 6.38*t}} \qquad \text{(equation 8);}$$

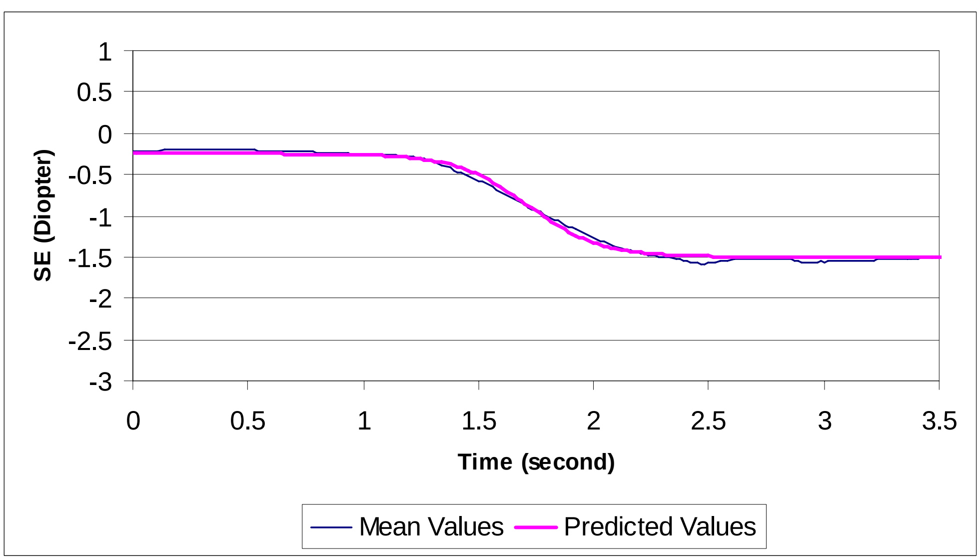


Figure 63: Mean and predicted values for YBB

Similarly, logistic regression was conducted on the rest of the conditions. Table 45 elaborates the specific values of Parameter a, b, and M, and the R^2 for the logistic regression under each combination of age group, light intensity, and light chromaticity within the scope of the study.

Table 45: Parameters of the logistic regression

Age Group	**Light Intensity**	**Light Chromaticity**	**a**	**b**	**M**	**R^2**	**Model: Predicted SE value =**
Younger Group	Bright	Blue	10.14	-5.91	1.25	>.99	$-0.25-\frac{1.25}{1+e^{10.94-6.38*t}}$
		Red	11.50	-6.98	1.25	>.99	$-0.25-\frac{1.25}{1+e^{11.5-6.98*t}}$
	Dark	Blue	9.67	-5.92	0.95	>.99	$-0.25-\frac{0.95}{1+e^{9.67-5.92*t}}$
		Red	12.94	-7.86	0.95	>.99	$-0.25-\frac{0.95}{1+e^{12.94-7.86*t}}$
Middle-aged Group	Bright	Blue	9.33	-4.76	1.25	>.99	$-0.25-\frac{1.25}{1+e^{9.33-4.76*t}}$
		Red	8.59	-4.45	1.25	>.99	$-0.25-\frac{1.25}{1+e^{8.59-4.45*t}}$
	Dark	Blue	7.70	-4.07	0.55	>.99	$-0.25-\frac{0.55}{1+e^{7.7-4.07*t}}$
		Red	5.20	-2.46	0.95	>.99	$-0.25-\frac{0.95}{1+e^{5.2-2.46*t}}$
Older Group	Bright	Blue	17.51	-9.39	0.25	>.99	$-0.25-\frac{0.25}{1+e^{17.51-9.39*t}}$
		Red	20.56	-10.90	0.25	>.99	$-0.25-\frac{0.25}{1+e^{20.56-10.9*t}}$
	Dark	Blue	28.73	-14.82	0.13	>.99	$-0.25-\frac{0.13}{1+e^{28.73-14.82*t}}$
		Red	32.52	-16.91	0.13	>.99	$-0.25-\frac{0.13}{1+e^{32.52-16.91*t}}$

4.4 Validation of the findings of the study

In order to validate the results of the study, a validation experiment was conducted. In this validation experiment, an instrument cluster (Figure 64) was used as a new near target, which could display a blue high beam signal and a red airbag signal one at a time and of a variety of intensities. Except for the new near target and the exclusion of Condition 1 (the adjustable location for the near target), all the procedures and the setup of the devices were kept exactly the same as those for the previous experiment as described in Section 3.5 Procedures. The hypothesis of this experiment was that participants should have a similar accommodative performance (measured by the six parameters) when the signals displayed on the instrument cluster had similar intensity and chromaticity as the stimuli used in “the previous experiment” (this term is used to refer to the original experiment throughout this section).

Figure 64: The instrument cluster

4.4.1 Sample size calculation for the validation experiment

The sample size required for this experiment was estimated based on the data collected from the previous experiment. Among the six dependent variables (i.e., MOA, RAT, RTI, ATI, PV, and Time%), the inter-subject variability of reaction time (RAT) among the three age groups was used to calculate the power for this validation experiment. The reason to use RAT for the power analysis, instead of the other parameters, was that: 1) the previous experiment suggested that RAT was a good indicator of the dynamic aspects of an accommodation process, and 2) the results of this parameter in the previous experiment aligned closely with the published values from the literature. Hence, the power of the test was determined by focusing on sample sizes large enough to detect differences in reaction time among younger, middle-aged, and older individuals with high probability (>0.70).

Using the method described in Section 3.1 Participants, the results of RAT in previous experiment suggested that the effect size of the aging effect on RAT was 1.378, and a sample size of 9 (3 participants from each group) should be sufficient to detect the specified differences with risks of Type I error of 0.05 and Type II error of < 0.20 (Power > 0.80). Therefore, a total of 9 participants were recruited for the purpose of data validation: 3 younger participants (mean = 21.4 yrs, s.d. = 1.02 yrs), 3 middle-aged participants (mean = 46.4 yrs, s.d. = 2.74 yrs), and 3 older participants (mean = 65.9 yrs, s.d. = 1.16 yrs). The results suggested that the actual power was greater than 0.80.

4.4.2 Validation of the findings

Table 46 elaborates the lighting conditions displayed by the instrument cluster. It suggests that the chromaticity levels of light projected by the high beam and airbag signals were fairly close to the chromaticity levels of the Maltese cross displayed by the laptop. Due to the physical configuration of the bulbs used to light up the signals, the two intensity levels were chosen at 5 and 1 cd/m^2. While the two intensities levels were different from those displayed by the laptop, the proportion between the bright level and the dark level was controlled at the same level for the two experiments, which was expected to create a similar effect of light intensity on the dynamic accommodative performance for this experiment.

Table 46: Comparison of the lighting conditions

		The Instrument Cluster	The Maltese Cross
Light Intensity	Bright	5 cd/m^2	100 cd/m^2
	Dark	1 cd/m^2	20 cd/m^2
Light Chromaticity	Blue	0.176, 0.165, 3.62 cd/m^2	0.152, 0.130, 11.9 cd/m^2
	Red	0.601, 0.352, 4.02 cd/m^2	0.524, 0.333, 11.2 cd/m^2

In general, the results of the validation experiment indicated that similar to the previous experiment, there were statistically significant effects of aging, light intensity and light chromaticity on the dynamic accommodative performance. The MANOVA results of the validation experiment and the previous experiment for the general effects of age, light intensity and chromaticity are summarized in Table 47.

Table 47: Comparison of MANOVA test for the general effects of age, light intensity, and chromaticity between the validation experiment and the previous experiment

	Validation		**Previous**	
Source	**F Value**	**Prob > F**	**F Value**	**Prob > F**
Age	$F_{(24,26)}$=45.95	**<.0001**	$F_{(24,32)}$=21.71	**<.0001**
Intensity	$F_{(12,13)}$=20.91	**<.0001**	$F_{(12,16)}$=85.20	**<.0001**
Color	$F_{(12,13)}$=4.90	**0.0039**	$F_{(12,16)}$=43.67	**<.0001**
Age*Intensity	$F_{(24,26)}$=2.00	**0.0437**	$F_{(24,32)}$=6.67	**<.0001**
Age*Color	$F_{(24,26)}$=0.42	0.9816	$F_{(24,32)}$=2.81	**0.0034**
Intensity*Color	$F_{(12,13)}$=0.87	0.5946	$F_{(12,16)}$=2.96	**0.0225**
Age*Intensity*Color	$F_{(24,26)}$=1.60	0.3602	$F_{(24,32)}$=1.60	0.1056

Table 48 summarizes the univariate ANOVA tests on each of the dependent variables for the two experiments. In general, it was consistent with the previous experiment that aging and different light intensities led to the change of the six parameters. However, the effect of light chromaticity was found to be statistically significant only in some of the dependent variables, and there were no statistically significant interaction effects on any of the six parameters.

Table 48: Comparison of univariate ANOVA tests for the effects of age, light intensity, and chromaticity between the validation experiment and the previous experiment

MOA	**Validation**		**Previous**	
Source	**F Value**	**Prob > F**	**F Value**	**Prob > F**
Age	$F_{(4,10)}=17.21$	**0.0002**	$F_{(4,52)}=45.21$	**<.0001**
Intensity	$F_{(2,5)}=18.89$	**0.0047**	$F_{(2,26)}=164.34$	**<.0001**
Color	$F_{(2,5)}=1.20$	0.3764	$F_{(2,26)}=7.91$	**0.0021**
Age*Intensity	$F_{(4,10)}=2.75$	0.0889	$F_{(4,52)}=16.47$	**<.0001**
Age*Color	$F_{(4,10)}=0.04$	0.9967	$F_{(4,52)}=0.20$	0.9397
Intensity*Color	$F_{(2,5)}=0.17$	0.8498	$F_{(2,26)}=5.09$	**0.0136**
Age*Intensity*Color	$F_{(4,10)}=0.51$	0.7313	$F_{(4,52)}=2.52$	0.0522
RAT	**Validation**		**Previous**	
Source	**F Value**	**Prob > F**	**F Value**	**Prob > F**
Age	$F_{(4,10)}=9.91$	**0.0017**	$F_{(4,52)}=32.48$	**<.0001**
Intensity	$F_{(2,5)}=7.48$	**0.0314**	$F_{(2,26)}=57.91$	**<.0001**
Color	$F_{(2,5)}=2.02$	0.2274	$F_{(2,26)}=9.62$	**0.0007**
Age*Intensity	$F_{(4,10)}=2.89$	0.0540	$F_{(4,52)}=8.17$	**<.0001**
Age*Color	$F_{(4,10)}=0.13$	0.9671	$F_{(4,52)}=1.34$	0.2674
Intensity*Color	$F_{(2,5)}=3.92$	0.0663	$F_{(2,26)}=0.81$	0.4554
Age*Intensity*Color	$F_{(4,10)}=1.08$	0.4171	$F_{(4,52)}=1.01$	0.4115
RTI	**Validation**		**Previous**	
Source	**F Value**	**Prob > F**	**F Value**	**Prob > F**
Age	$F_{(4,10)}=3.66$	**0.0491**	$F_{(4,52)}=3.10$	**0.0230**
Intensity	$F_{(2,5)}=12.89$	**0.0106**	$F_{(2,26)}=53.43$	**<.0001**
Color	$F_{(2,5)}=32.32$	**0.0014**	$F_{(2,26)}=29.53$	**<.0001**
Age*Intensity	$F_{(4,10)}=1.38$	0.3081	$F_{(4,52)}=8.74$	**<.0001**
Age*Color	$F_{(4,10)}=2.59$	0.1011	$F_{(4,52)}=5.36$	**0.0011**
Intensity*Color	$F_{(2,5)}=0.68$	0.5486	$F_{(2,26)}=2.13$	0.1394
Age*Intensity*Color	$F_{(4,10)}=0.53$	0.7178	$F_{(4,52)}=1.72$	0.1594
ATI	**Validation**		**Previous**	
Source	**F Value**	**Prob > F**	**F Value**	**Prob > F**
Age	$F_{(4,10)}=8.69$	**0.0027**	$F_{(4,52)}=7.51$	**<.0001**
Intensity	$F_{(2,5)}=44.59$	**0.0006**	$F_{(2,26)}=447.43$	**<.0001**
Color	$F_{(2,5)}=11.83$	**0.0127**	$F_{(2,26)}=99.83$	**<.0001**

Age*Intensity	$F_{(4,10)}$=1.38	0.3079	$F_{(4,52)}$=7.80	**<.0001**
Age*Color	$F_{(4,10)}$=0.85	0.5230	$F_{(4,52)}$=11.22	**<.0001**
Intensity*Color	$F_{(2,5)}$=1.16	0.3852	$F_{(2,26)}$=2.51	0.1008
Age*Intensity*Color	$F_{(4,10)}$=0.17	0.9464	$F_{(4,52)}$=1.12	0.3591

PV	**Validation**		**Previous**	
Source	**F Value**	**Prob > F**	**F Value**	**Prob > F**
Age	$F_{(4,10)}$=6.29	**0.0085**	$F_{(4,52)}$=9.06	**<.0001**
Intensity	$F_{(2,5)}$=5.76	**0.0455**	$F_{(2,26)}$=49.83	**<.0001**
Color	$F_{(2,5)}$=0.89	0.4676	$F_{(2,26)}$=43.07	**<.0001**
Age*Intensity	$F_{(4,10)}$=0.72	0.5992	$F_{(4,52)}$=3.95	**0.0071**
Age*Color	$F_{(4,10)}$=1.57	0.2556	$F_{(4,52)}$=5.88	**0.0006**
Intensity*Color	$F_{(2,5)}$=0.07	0.9341	$F_{(2,26)}$=13.42	**<.0001**
Age*Intensity*Color	$F_{(4,10)}$=0.04	0.9969	$F_{(4,52)}$=1.73	0.1580

Time%	**Validation**		**Previous**	
Source	**F Value**	**Prob > F**	**F Value**	**Prob > F**
Age	$F_{(4,10)}$=3.46	**0.0492**	$F_{(4,52)}$=7.82	**<.0001**
Intensity	$F_{(2,5)}$=15.92	**0.0068**	$F_{(2,26)}$=67.92	**<.0001**
Color	$F_{(2,5)}$=8.93	**0.0224**	$F_{(2,26)}$=93.84	**<.0001**
Age*Intensity	$F_{(4,10)}$=0.65	0.6423	$F_{(4,52)}$=1.55	0.2024
Age*Color	$F_{(4,10)}$=0.22	0.9203	$F_{(4,52)}$=1.59	0.1933
Intensity*Color	$F_{(2,5)}$=4.56	0.0745	$F_{(2,26)}$=1.54	0.2340
Age*Intensity*Color	$F_{(4,10)}$=0.42	0.7882	$F_{(4,52)}$=2.08	0.0973

5. Discussion

The results of the study are discussed as follows: 1) the findings of the study are summarized and used to evaluate the hypotheses of the study, along with comparisons of the results with the literature; 2) a theoretical biomechanical and neural model is thereafter presented to help explain the age-related accommodation loss under different lighting conditions; 3) the importance of the six dependent variables is discussed on the basis of the results; and 4) the applications of the findings (including the logistic equations and the validation results) are clarified.

5.1 General findings and hypothesis testing

In general, the objective of the study was to investigate the age-related dynamic accommodative performance under different lighting conditions. The hypotheses of the study were: 1) the age-related changes of the eye will lead to the change of the dynamic accommodative performance; 2) light of different intensities will influence one's dynamic accommodative performance; 3) light of different chromaticities will result in different dynamic accommodative performances; and 4) light of different intensities and chromaticities will change the age-related accommodation loss. As any changes in the six dynamic aspects (i.e., MOA, RAT, RTI, ATI, PV, and Time%) could imply the change of the dynamic accommodative performance, the results of the MANOVA test (Table 4) were used to evaluate the four hypotheses of the study. Overall, the hypotheses of the study were supported by the results.

5.1.1 Hypothesis 1: the effect of aging

The first hypothesis of the study was that the age-related changes of the eye will lead to the change of the dynamic accommodative performance. The MANOVA results (Table 4) indicated that there were statistical significant differences in the accommodative performance among the three age groups. Subsequent ANOVA tests also suggested that with the advancing of age, the magnitude of accommodation declined (Figure 25), the participants spent a longer time to react to the stimulus (Figure 31), and the accommodation response became longer and slower (Figures 37, 43, 49, & 55). One explanation is the apparent physiological changes of the biomechanical plant[10], including increased lenticular hardness and decreased ciliary muscular tension. While the literature suggests that these changes can be considered a major contributing factor to the age-related accommodation loss (Donders, 1864, Duane, 1912, Hofstetter, 1965, Ramsdale and Charman, 1989, and Koretz, et al., 1989, Mordi and Ciuffreda, 1998), Ciuffreda, et al. (2000) speculates that the increased reaction time for the accommodation response is likely not primarily due to accommodation plant limitations, nor to peripheral neuromuscular transmission delays, but rather to a delay in central higher-order neural processing time. In other words, the effect of aging on the dynamic accommodative performance may be viewed as a combination of the effect of aging on the biomechanical structure of the eye and that on the neurons involved in human visual perception. This rationale is further elucidated in Section 5.2, A biomechanical and neural model of an accommodation process.

5.1.2 Hypothesis 2: the effect of light intensity

The second hypothesis of the study was that light of different intensities will influence one's dynamic accommodative performance. The MANOVA results (Table 4) indicated that there were statistical significant differences in the accommodative performance associated with the intensity of light. Specifically, similar to the effect of aging, decreased light intensity (i.e., from 100 cd/m^2 to 20 cd/m^2) also resulted in lower magnitude and speed of accommodation (Figures 26, 50, & 56) and longer reaction and response times (Figures 32, 38, & 44).

While the age-related accommodation loss may be considered to be largely ascribed to the biomechanical changes of the accommodation plant (i.e., the crystalline

[10] As the lens and surrounding muscles work together during accommodation, they are called a "plant".

lens, the ciliary muscle, and the Zonular attachments), the effect of light on accommodation is mainly due to the neural characteristics of the eye, especially the cone photoreceptors on the retina. Specifically, information of defocus carried by light is transmitted via cone signals, bipolar cells, and retinal ganglion cells to the lateral geniculate nucleus (LGN). This pathway is often referred to as the luminance pathway and 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. As a consequence, a lesser amount of accommodative stimulus is collected by cones and then transmitted to the visual cortex via the luminance pathway. Hence, reduced accommodative power with diminishing light intensity has been observed in many previous studies (Johnson, 1976, Rosenfield, 1993, Arumi et al., 1997, Jackson, et al., 1999). The decreased dynamic accommodative performance found in the current study also supported this argument. However, as this study is the first one to include the effect of light intensity on the dynamic aspects of accommodation, only reaction time under the dark condition (i.e., 20 cd/m^2) may be compared with previous results (Heron, et al., 2002, a target of 35 cd/m^2 used; Mordi and Ciuffreda, 2004, a target of 25 cd/m^2 used). It is suggested that reaction time from the current study (394.976 ± 121.239 ms) is similar to that from other studies (340 ± 100 ms, Heron, et al. 2002; 325 ~ 530 ms, Mordi and Ciuffreda, 2004).

5.1.3 Hypothesis 3: the effect of light chromaticity

Besides the luminance pathway, two chromatic pathways are also responsible for transmitting retinal input to the visual cortex via the LGN (Rucker and Kruger, 2004). They are the long- and middle-wavelength sensitive pathway and the short-wavelength sensitive pathway. The long- and middle-wavelength sensitive pathway transmits inputs from L-cones and M-cones, while the short-wavelength sensitive pathway depends mainly on S-cones. Previous studies have shown that some participants can accommodate using only short wavelength cones, while others show a reduced accommodative performance (Aggarwala, et al., 1995; Fincham, 1951; Rucker and Kruger, 2001). According to Rucker and Kruger (2001), the accommodation system may have color vision and deliberately let the blue image be myopic. In this sense, considering the much smaller amount of S-cones than that of L- or M- cones on the retina (Schiffman, 2005), the short-wavelength sensitive pathway may not act as dominantly as the long- and middle-wavelength sensitive pathway. In other words, it appears that the short-wavelength sensitive pathway may serve only as a supplementary pathway during the accommodation process.

In order to evaluate the chromaticity effect, the third hypothesis of the study focused on the accommodative performance associated with different light chromaticities. The MANOVA results (Table 4) indicated that there were statistically significant differences in the accommodative performance associated with the two light chromaticity levels (i.e., blue vs. red). Similar to the literature, the current study indicated that the participants had difficulty in focusing when looking at the blue target, but not at the red target. The investigation of the dynamic aspects of accommodation further suggested that the participants reacted more quickly (Figure 33) and accommodated faster (Figures 39, 45, 51, & 57) when the red target was displayed. Therefore, possibly due to the existence of the long- and middle-wavelength sensitive pathway and the short-wavelength sensitive pathway, the results of the study suggested that light of different chromaticities, especially of distinct wavelengths (e.g., blue, short wavelength vs. red, long wavelength), may lead to the change of the dynamic accommodative performance. Although implicated, further study evaluating the neural pathways in relation to wavelength characteristics is needed to elucidate this statement.

5.1.4 Hypothesis 4: the interaction effects among aging, light intensity, and light chromaticity

As discussed in the literature review, aging has an adverse effect on the photoreceptors on the retina. When a person gets older, the photoreceptors start to degenerate and lose their functionality. It starts with loss of rods and then cones. Due to the accelerating loss of cones at older ages (Curcio, et al., 1996), older adults, compared with younger and middle-aged counterparts, are expected to exhibit a more remarkable change of the dynamic accommodative performance when the ambient conditions are changed from daytime to nighttime or images of different colors are displayed. In order to test this hypothesis, the interaction effects between aging and different lighting conditions were assessed. The results of the study indicated clearly that there were statistically significant interaction effects between aging and light intensity and between aging and light chromaticity (Table 4, Figure 28, 46). However, as only a little accommodative ability remains in the elderly population (Duane, 1912, Hamasaki, et al., 1956, Mordi and Ciuffreda, 1998), the accelerating deterioration of the accommodative performance for the older adults as suggested by the literature review was not found in all of the six dependent parameters.

For example, the results of the magnitude of accommodation (MOA) showed that the significant interaction effect between aging and light intensity (Figure 28) was due to: 1) the increased decline of MOA under the nighttime conditions for the middle-aged participants, compared with that for the younger participants, and 2) the lesser decline of MOA for the older participants when the intensity of light was reduced from the daytime to nighttime conditions. The increased decline of MOA for the middle-aged participants helped support that the loss of cones with aging might result in a further decrease of the accommodative performance. However, the lesser decline of MOA for the older participants failed to suggest that the accelerating loss of cones at older ages might lead to any further decline of the accommodation response. Similar results were also found in the interaction effect between aging and light intensity on RTI (Figure 40), ATI (Figure 46), PV (Figure 52), and Time% (Figure 58). However, the interaction effect on RAT (Figure 34) indicated that the older participants reacted more slowly, and this lag increased with the advancing of age, which seemed to be consistent with the rationale based on the literature review. Hence, possibly due to the little accommodative power remaining in the older participants, the mixed findings of the study failed to draw any conclusions about the rationale for the statistically significant interaction effect between aging and light intensity on the dynamic accommodative performance.

On the other hand, as L- and M- cones are more dominant and active than S-cones (Kruger, et al., 2005, Rucker and Kruger, 2004, 2006), the loss of cones due to aging might affect one's accommodation on images of long- and middle- wavelength light differently from that on images of short-wavelength light. Nevertheless, the results of the present study cannot fully support this statement. Though less improvement of accommodation was found in terms of the six parameters for the older group when the target was switched from blue to red (Figures 29, 35, 41, 47, 53, & 59), this might likely be due to the little accommodative ability remaining within the older group, rather than the change of cones with age. Therefore, as the current study did not measure directly the distribution of cones on the retina, the findings of the study can only imply indirectly the relationship between the advancing of age and the cone photoreceptors on the retina. In this sense, though the results of the study indicated some interaction effects on accommodation between aging and light of different intensities or chromaticities, the findings of the study were not able to elucidate how the advancing of age might result in the actual changes of the photoreceptors on the retina. Future study is needed to explore this area.

In summary, the results of the study indicated clearly that the effects of aging, light intensity, and light chromaticity all had significant impacts on the dynamic accommodative performance of the eye. The causes of these effects were mainly ascribed to the age-related physiological changes of the eye and the potentially age-related neural changes in the nervous system. Based on the results, a biomechanical and neural model of an accommodation process was proposed, following comparisons of the results with the literature.

5.1.5 Comparisons of the results with the literature

In spite of the well-documented age-related loss of the static amplitude of accommodation (Donders, 1864, Duane, 1912, Hamasaki, et al., 1956, Hofstetter, 1965, Charman, 1989, Ramsdale and Charman, 1989, and Koretz, et al., 1989), much less attention has been devoted to understanding the age-related loss of dynamic accommodation. This is probably due to the difficulties of measuring the relatively short and quick accommodation time associated with abrupt changes in target distances. Nevertheless, the age-related increase in hardness of the lens measured by Glasser and Campbell (1998), and the changes in the ciliary body and the geometry of the Zonular attachments (Duane, 1922, Weale, 1962) can be inferred to limit both the amplitude and the speed at which the lens can respond to a certain accommodative demand for the elderly.

Early studies using fairly rough reaction-time methods and step stimuli (Allen, 1956, Temme and Morris, 1989) found that overall response times were longer for older adults. Although Sun et al. (1988), using an infra-red optometer and a stimulus change from 1 to 4 Diopters, suggested that reaction time changed little with age, deterioration in accommodation dynamics with age was found by Schaeffel, et al. (1993) via photoretinoscopy, Beers and van der Heijde (1996) via an ultra-sound system, and Ciuffreda, et al. (2000) via optometry. Nevertheless, no agreement has been reached on the normal range of the dynamic characteristics of accommodation. Further, there is no study similar to the current one covering such a wide range of age (20-69 years) and taking into consideration the effects of both light intensity and light chromaticity.

The age-related changes of the magnitude of accommodation found in the present study aligned with the normal range of the amplitude of accommodation in the literature (Table 49). As the amplitude of accommodation is defined by the nearest and farthest points the eye can focus on, and the unit of Diopter is derived from the reciprocal of a meter, an amplitude of 9 Diopters, for example, 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 the literature (Table 49) suggested that both younger and middle-aged adults should have the ability to accommodate from 4 m to 70 cm on the average. Since the results of the magnitude of accommodation found in the current study also indicated that those two age groups could accommodate from 4 m to 70 cm, which corresponded to a diopter value of 1.18 Diopters (1/0.7-1/4 = 1.18), the current study aligned with the literature in terms of the magnitude of accommodation. Additionally, the results for the older group were compared directly with the normal range of the amplitude of accommodation for the elderly. This is because the measure of the magnitude of accommodation for the older group was virtually a measure of their amplitude of accommodation in the current study, as the stimulus for accommodation was expected to trigger the maximum amount of their accommodative ability. Therefore, Table 49 indicates that the results of the age-related changes of the magnitude of accommodation found in the current study were consistent with the literature.

Table 49: Comparison of MOA between the current study and the literature

Age Group	**The Current Study MOA (Diopter)**	**The 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

Additionally, reaction time was also in agreement with previous investigations (Table 50). Despite that a variety of sample sizes and age ranges were used in the previous studies (Sun, et al., 1988, Ciuffreda, et al., 2000, and Heron, et al., 2002), Table 50 reveals that reaction time measured in the present study was fairly close to that documented in the literature.

Table 50: Comparison of RAT between the current study and the literature

Age Group	**The Current Study RAT (ms)**	**The Literature RAT (ms)**
Younger Group (20-29 years)	238.247 ± 37.319	340 ± 100 (Heron, et al., 2002; 19 subjects; age: 18-49 years) 300 - 500, and avg. +2.5 / year (Ciuffreda, et al., 2000; 72 subjects; age: 21-50 years) avg. 325 (Sun, et al., 1988; 6 subjects; age: 13-46 years)
Middle-aged Group (40-49 years)	380.940 ± 53.528	
Older Group (60-69 years)	472.686 ± 75.153	

On the other hand, since no literature is available for describing how RTI, ATI, PV, and Time% are affected by the advancing of age or light of different intensities or chromaticities, Table 51 summarizes the normal range of the six parameters solely based on the current study. Based on Table 51, three design guidelines for visual signal design were developed (see Section 5.4.3 Guidelines for visual signal design).

Table 51: Normal range of MOA, RAT, RTI, ATI, PV, and Time%

Age Group		MOA (Diopter)	RAT (ms)	RTI (ms/m)	ATI (ms/m)	PV (Diopter/sec)	Time%
Younger Group		1.137 ± 0.205	238.247 ± 37.319	343.751 ± 47.473	415.947 ± 55.049	1.723 ± 0.601	39.807 ± 7.807
Middle-aged Group		1.005 ± 0.277	380.940 ± 53.528	388.720 ± 49.985	504.156 ± 62.320	0.939 ± 0.577	32.954 ± 6.389
Older Group		0.204 ± 0.112	472.686 ± 75.153	440.858 ± 98.133	661.600 ± 147.566	0.462 ± 0.253	27.787 ± 5.852
Light Intensity							
Bright	Young	1.271 ± 0.138	224.188 ± 30.863	318.253 ± 41.288	386.189 ± 46.913	1.878 ± 0.625	36.228 ± 7.096
	Middle	1.239 ± 0.121	350.646 ± 40.170	356.143 ± 34.481	462.399 ± 41.003	1.127 ± 0.658	30.457 ± 3.970
	Old	0.244 ± 0.121	423.981 ± 55.075	438.831 ± 107.020	636.282 ± 145.697	0.550 ± 0.273	24.026 ± 3.978
Dark	Young	1.003 ± 0.171	252.304 ± 38.252	369.250 ± 39.076	445.706 ± 46.057	1.568 ± 0.541	43.385 ± 6.845
	Middle	0.771 ± 0.167	411.235 ± 48.038	421.297 ± 41.171	545.914 ± 51.082	0.752 ± 0.412	35.451 ± 7.357
	Old	0.165 ± 0.086	521.390 ± 59.509	442.885 ± 89.695	686.918 ± 146.857	0.374 ± 0.198	31.546 ± 4.954
Light Chromaticity							
Blue	Young	1.099 ± 0.215	253.647 ± 38.333	373.783 ± 34.110	450.646 ± 42.620	1.578 ± 0.468	42.283 ± 7.250
	Middle	0.976 ± 0.282	399.863 ± 51.257	408.475 ± 46.935	529.646 ± 57.936	0.740 ± 0.446	34.579 ± 6.259
	Old	0.178 ± 0.119	476.769 ± 79.482	445.852 ± 85.600	669.108 ± 142.728	0.421 ± 0.245	29.814 ± 5.908
Red	Young	1.175 ± 0.190	222.846 ± 29.414	313.720 ± 39.393	381.249 ± 43.040	1.868 ± 0.685	37.330 ± 7.638
	Middle	1.035 ± 0.271	362.017 ± 49.418	368.965 ± 45.360	478.668 ± 56.374	1.139 ± 0.628	31.329 ± 6.172
	Old	0.231 ± 0.099	468.601 ± 71.337	435.864 ± 110.130	654.091 ± 153.697	0.504 ± 0.256	25.758 ± 5.102

5.2 A biomechanical and neural model of an accommodation process

Ocular accommodation, the focusing mechanism of the human eye, operates by changing the shape of the crystalline lens in response to the constriction of the ciliary muscle. Forces applied to the lens are changed during accommodation by agonist–antagonist interactions between the ciliary muscle and the choroid respectively (Helmholtz, 1866). These forces are transferred via the suspensory Zonular fibers to the lens and its capsule (Beers and van der Heijde, 1994). Age-related changes in the biomechanics of this accommodative plant (Figure 65) include an increase in the modulus of elasticity of the lens capsule (Krag, et al., 1997), an increase in the viscosity of the lens, and a loss of tension of the Zonular fibers (Glasser and Campbell, 1998).

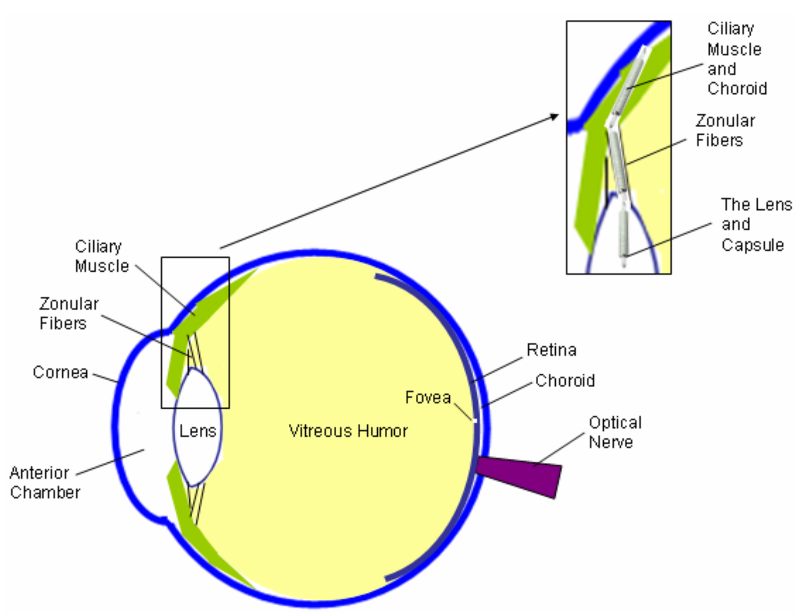


Figure 65: The biomechanical accommodative plant

On the other hand, 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). In other words, this nucleus may act as an executive center that carries the commands from the visual cortex and controls the biomechanical accommodative plant to create a proper optical power of the eye for the target image.

Hence, along with the knowledge of the three pathways that transmit the stimulus for accommodation to the visual cortex (see Sections 5.1.2 & 5.1.3), the mechanism of the accommodation process of the eye may be illustrated as follows (Figure 66):

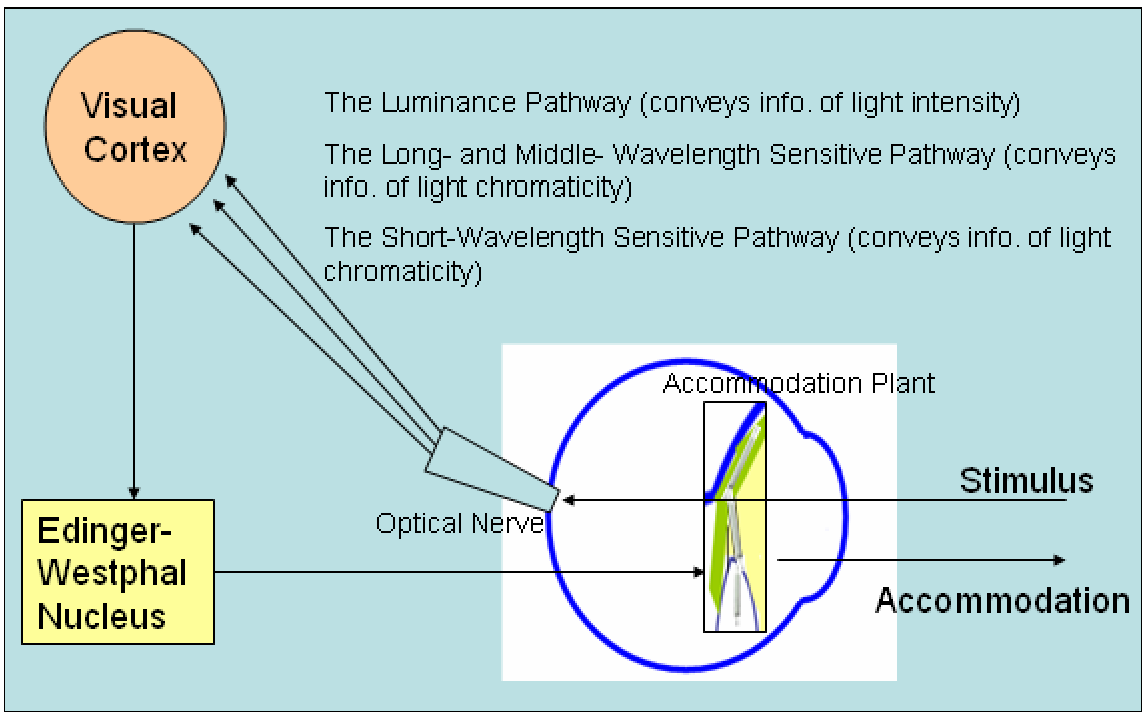


Figure 66: The mechanism of an accommodation process

Specifically, with the onset of a stimulus for accommodation (e.g., to look at the instrument cluster while driving), the stimulus is collected by the cones on the retina and transmitted to the visual cortex via the luminance pathway, the long- and middle-wavelength sensitive pathway, and the short-wavelength sensitive pathway which carry various information about the stimulus (e.g., its intensity and chromaticity). Then the brain (specifically, the visual cortex) sends a command for accommodation to the accommodative plant via the oculomotor nerve (specifically, the Edinger-Westphal nucleus). Finally, the accommodative plant responds accordingly by changing the curvature of the crystalline lens via the ciliary muscles and the Zonular fibers.

As light of different intensities and chromaticities are transmitted to the visual cortex differently via the three pathways (Rucker and Kruger, 2004), the accommodative performance may change with different lighting conditions as found in the current study. More importantly, as the advancing of age results in a variety of changes of the eye, including the hardening of the lens (Gullstrand, 1909), the loss of muscle tension (Duane, 1922), the recession of cones (Curcio, et al., 1996), and the decline of the processing time of the central neural system (Mordi and Ciuffreda, 2004), the accommodative performance is greatly subject to age-related changes of the eye. The profound effects of aging on the accommodative performance found in the present study also support this argument.

Therefore, a biomechanical and neural model was developed based on the findings of the study and the literature to elaborate the mechanism of the accommodation process of the eye (Figure 67). In this model, the accommodation process is divided into two modules, a neural module and a biomechanical module. The neural module explains how the neurons are involved in an accommodation response, while the biomechanical module executes the actual biomechanical changes of the eye according to the information provided by the neural module. The neural module was constructed based on the findings of the study (especially, the effects of light intensity and chromaticity) and the current knowledge of the accommodation-related neurons. The biomechanical module was based on the physiological mechanism of accommodation described by Beers and van der Heijde (1994). According to the effects of aging, light intensity, and light chromaticity found in the present study, the two modules formed the biomechanical and neural model to depict one's accommodation process.

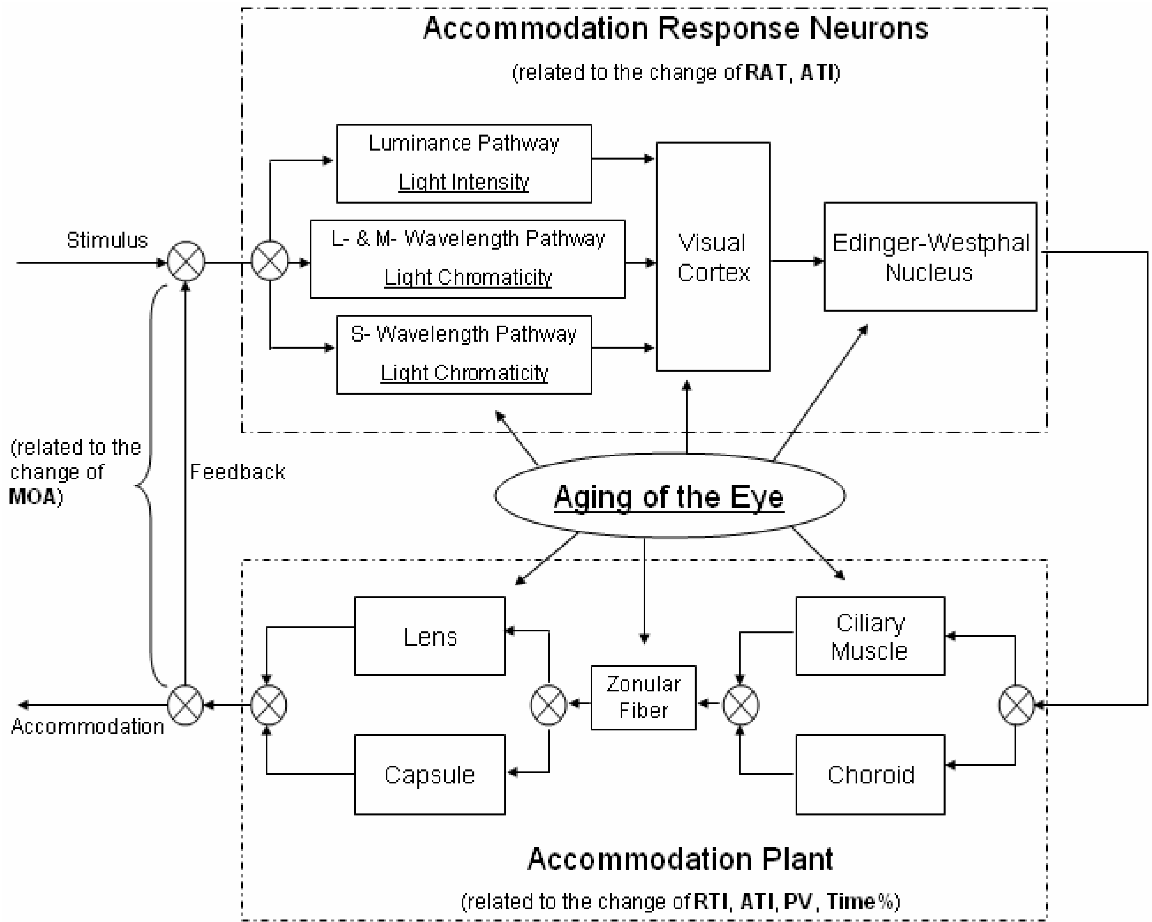


Figure 67: A biomechanical and neural model of an accommodation process

The uniqueness of this model can be ascribed not only to the comprehensive view of how accommodation is triggered and executed but also to the indication of the roles of aging, light intensity, and light chromaticity in this process. Since the effect of aging on accommodation turned out to be so profound in the current study, the model places the effect of aging in a position indicating that the advancing of age may have an adverse effect on every phase of the accommodation process, which is supported by the literature (Helmholtz, 1866, Jampel and Mindel, 1967, Beers and van der Heijde, 1994, Kourouyan and Horton, 1997). On the other hand, as the literature suggests that the statistically significant effects of light intensity and light chromaticity on dynamic accommodative performance may result from the presence of the luminance, long- and middle- wavelength sensitive, and short-wavelength sensitive pathways (Kruger, et al., 2005, Stockman, et al., 2005), the model locates the light intensity factor and the light chromaticity factor in the neural module[11]. This suggests that different light intensities or chromaticities may convey different information to the visual cortex and trigger accommodation differently. That is, the decline of light intensity reduces the functionality of cones which may impair the luminance pathway and result in a reduced accommodative performance. Also, the use of the blue image (short-wavelength light) may be transmitted mainly by the short-wavelength sensitive pathway and thus cannot trigger accommodation as efficiently as those images activating the long- and middle-wavelength sensitive pathway. Moreover, as cones start to degenerate with aging, the model links the aging of the eye with the three pathways, which takes into account the interactions between aging, light intensity, and light chromaticity as found in the study.

As for the six parameters extracted from the recorded dynamic accommodation process, they are positioned differently in the model on the basis of their definitions. The magnitude of accommodation (MOA), as a measure of the difference between the stimulus of accommodation and the actual accommodated distance, is located outside of the neural and the biomechanical modules, suggesting its relation to both the functions of the neural and biomechanical characteristics of the eye. On the other hand, as reaction time (RAT) may be largely due to the processing time of the neural system (Ciuffreda, et al., 2000), it is positioned in the neural module separated from the response time index (RTI), the peak velocity (PV), and the percentage of time to reach the peak (Time%), which are located within the biomechanical module. As the accommodation time index (ATI) is determined by both RAT and RTI, it appears in both of the modules.

In summary, based on the findings of the study, a biomechanical and neural model was developed to help describe a complete dynamic accommodation process with the inclusion of the aging factor, the light intensity factor, and the light chromaticity factor. The model indicates that when the stimulus of accommodation reaches the retina, the information about the stimulus (e.g., its intensity and chromaticity) is transmitted to

[11] Although the age-related changes of the lens (e.g., becoming more opaque) may contribute to the effects of light intensity and chromaticity, the screening test minimized this possibility which guaranteed that all of the eyes tested were clear and healthy enough.

the visual cortex for processing via the three pathways. Then the visual cortex sends a command for accommodation to the Edinger-Westphal nucleus, which controls the lens and the surrounding muscles to achieve an anticipated accommodative level. The success of this process can be assessed not only by the final accommodated distance (as measured by the magnitude of accommodation) but also by the dynamic aspects involved in the process. Specifically, the performance of the accommodation response neurons may result in different reaction times and accommodation time indices. The characteristics of the accommodation plant may influence the response time index, the accommodation time index, the peak velocity, and the percentage of time to reach the peak. As the neurons and the biomechanical plant are subject to aging and different levels of light intensity and chromaticity, the model links the dynamic accommodative performance found in the current study with the contributing factors of aging and different lighting conditions.

5.3 The importance of using MOA, RAT, RTI, ATI, PV, and Time%

The present study evaluated one's dynamic accommodative performance via the magnitude of accommodation (MOA), reaction time (RAT), the response time index (RTI), the accommodation time index (ATI), the peak velocity (PV), and the percentage of time to reach the peak (Time%). Although each of the parameters described a certain aspect of the dynamic accommodative performance, it would be beneficial to future research to assess the effectiveness of each parameter. In other words, it is important to determine whether it was necessary to use all of the parameters for the study of dynamic accommodation. As such, the correlations among the six parameters and the post hoc effect sizes of the independent variables on each parameter were calculated. Table 52 and Table 53 list the correlation results and the effect sizes, respectively.

Table 52: The Pearson correlation coefficients among the six parameters

	MOA	**RAT**	**RTI**	**ATI**	**PV**	**Time%**
MOA	1.0000	-0.7265	-0.5642	-0.7417	0.6719	0.3909
RAT		1.0000	0.5446	0.7424	-0.7052	0.3084
RTI			1.0000	0.9363	-0.4181	0.0070
ATI				1.0000	-0.5625	-0.1596
PV					1.0000	0.2969
Time%						1.0000

Table 53: The post hoc effect sizes (calculated from means and standard deviations)

	Dependent Variables					
Independent Variables	**MOA**	**RAT**	**RTI**	**ATI**	**PV**	**Time%**
Age	2.0820	1.7433	0.6086	1.1505	1.0899	0.7370
Light Intensity	0.3098	0.2892	0.2611	0.2349	0.2052	0.4281
Light Chromaticity	0.0671	0.1145	0.2275	0.1624	0.1815	0.2529

Table 52 suggests that each of the six parameters was correlated to each other to a certain extent. This was likely due to the fact that the six parameters were extracted from the same accommodation response. However, there was no evidence indicating that any of the parameters could be eliminated from future study, because: 1) each of the independent variables had at least a medium effect size (0.25, Faul, et al., 2006) on nearly all of the parameters (Table 53), and 2) the six parameters conveyed three types of information (i.e., MOA about the actual accommodated distance; RAT, RTI, and ATI about the time of accommodation; and PV and Time% about the speed of accommodation). Therefore, in order to have a comprehensive view of one's dynamic accommodative performance, the six parameters are all necessary. If a detailed investigation of the speed of accommodation is of less concern, however, PV and Time% may be eliminated from the study in that RAT, RTI, and ATI can be used to imply the speed of accommodation. On the other hand, in terms of the three time-related parameters (i.e., RAT, RTI, ATI), all of these measures should be assessed so as to understand not only how long it takes the eye to start to accommodate but also how long it takes the eye to finish the accommodation. As RAT was not highly correlated to RTI ($r = 0.5446$, Table 52), ATI is useful to the understanding of how long a complete accommodation process will last.

In conclusion, all of the six parameters have their practical worth in the study of dynamic accommodative performance.

5.4 Applications of the study

The present study suggested that the age-related changes of the eye and light of different intensities or chromaticities would lead to changes of one's dynamic accommodative performance. In addition to investigating the effects of aging, light intensity, and light chromaticity, logistic regression was utilized to model the accommodation process quantitatively, and a validation experiment was conducted to validate the findings. This section discusses possible applications of those results.

5.4.1 The application of the logistic regression results

The purpose of conducting logistic regression is to discover a quantitative way to predict how the eye accommodates given that the age group and the lighting conditions are within the scope of the study. The high R^2 values (Table 45) and the comparison between the mean curve and the predicted one (Figure 63) indicate a good fit of the regression results. As such, it is expected that those logistic equations (Table 45) can be used to depict the actual change of the focus of the eye during accommodation. With the knowledge of the exact location of the focus at each point in time, Virtual Reality (VR) researchers may use the equations to improve the visual performance of VR images. Specifically, during accommodation, a person virtually does not focus on either the original image or the target image. As a result, he or she may not clearly see either of the images. In this sense, if accommodation is involved in a VR task, he or she literally cannot have good visual performance during that process. In order to solve this problem, VR designers can utilize those logistic equations to understand where the person is looking during accommodation. Then they can project VR images following the movement of the focus of the eye. That is, by means of those equations and VR technology, it may be possible that a person will not lose his or her visual performance even during accommodation.

Nevertheless, those equations may be applicable only under such conditions as those simulated in the present study in that only two levels of light intensity and two levels of light chromaticity were tested. Hence, caution should be taken when applying the equations to predict the accommodation process for conditions outside the scope of this study.

5.4.2 The usage of the validation results

In order to assess the generalizability of the findings of the study, a realistic target was used in the validation experiment. As the paradigm of the study was to evaluate dashboard reading behavior, an instrument cluster (Figure 64) was used to display realistic signals for accommodating. In spite of different light intensities displayed by the instrument cluster, as compared with those from the Maltese cross, the validation experiment suggested that, consistent with the findings of the original experiment, the advancing of age, the decrease of light intensity, and the use of bluish images would result in the decline of dynamic accommodative performance (in terms of MOA, RAT, RTI, ATI, PV, and Time%).

However, the effect of light chromaticity in the validation experiment was found to be statistically significant only on some of the dependent variables, and there were no statistically significant interaction effects on any of the six dependent variables. Possible explanations could be that: 1) for the validation experiment, the sample size was smaller than the previous experiment, which reduced the degree of freedom of the error terms, and 2) the intensity levels used (i.e., 5 cd/m^2 and 1 cd/m^2) were so low that the functionality of cones might be limited. That is, due to the decline of the cones' activity with the decrease of the intensity of light reaching them (Roorda and Williams, 1999, Schiffman, 2005), the efficiency of the long- and middle-wavelength sensitive pathway (controlled by L- and M-cones) may be reduced to a similar level as that of the short-wavelength sensitive pathway (controlled by S-cones). As a consequence, the blue and red signals displayed by the instrument cluster might trigger accommodation in a similar manner and not result in statistically significant differences of the dependent variables.

As such, the validation results suggested that the magnitude of the effects of aging, light intensity, light chromaticity, and their interactions was modulated by the actual lighting levels selected. Hence, caution should be taken when applying the findings of this study into other situations where lighting conditions are quite different from those tested in the study. For example, it may be speculated from the validation experiment that when the intensity of light is relatively low (e.g., 1-5 cd/m^2), the selection of the chromaticity of light may not matter in terms of its effect on dynamic accommodative performance.

5.4.3 Guidelines for visual signal design

The present study investigated the age-related dynamic accommodative performance under different conditions of light intensity and chromaticity. Derived from Table 51, Table 54 elaborates the differences of the means of MOA, RAT, RTI, ATI, PV, and Time% for each age group between the bright lighting condition and the dark lighting condition and between the use of the red image and the use of the blue image. The results could help suggest to what extent the change of light intensity or light chromaticity might lead to practically significant differences in dynamic accommodation. For example, although the increase of light intensity from dark (20 cd/m^2) to bright (100 cd/m^2) shortened reaction time, the response time index, and the accommodation time index for all of the age groups, the improvement of the response time index for the older group appeared to be negligible (i.e., a difference of 4.054 ms/m). Moreover, compared with the differences of the six parameters under different light intensities, the switch from the blue image to the red one seemed to have less impact on one's dynamic accommodative performance except for RAT, RTI, and ATI for the younger and middle-aged groups.

Table 54: Differences of the means of MOA, RAT, RTI, ATI, PV, and Time%

Light Intensity		**MOA (Diopter)**	**RAT (ms)**	**RTI (ms/m)**	**ATI (ms/m)**	**PV (Diopter/sec)**	**Time%**
Bright - Dark	Young	0.268	-28.116	-50.997	-59.517	0.310	-7.157
	Middle	0.468	-60.589	-65.154	-83.515	0.375	-4.994
	Old	0.079	-97.409	-4.054	-50.636	0.176	-7.520

Light Chromaticity		MOA (Diopter)	RAT (ms)	RTI (ms/m)	ATI (ms/m)	PV (Diopter/sec)	Time%
Red - Blue	Young	0.076	-30.801	-60.063	-69.397	0.290	-4.953
	Middle	0.059	-37.846	-39.510	-50.978	0.399	-3.250
	Old	0.053	-8.168	-9.988	-15.017	0.083	-4.056

Therefore, in order to have a better understanding of how different light intensities and chromaticities could practically influence one's accommodation, some of the results in Table 54 were compared with published driver's reaction times under various situations. Practical guidelines for visual signal design were developed thereafter.

Specifically, Consiglio, et al. (2003) investigated the effects of cellular telephone conversations and other potential interferences (i.e., listening to the radio or talking with a passenger) on reaction time in a braking response. Their study suggested that the increase of the reaction time to brake was at a magnitude of 16 ms between the control group (normal driving, 392 ms) and the radio group (408 ms), at a magnitude of 61 ms between the control group and the conversation with a passenger group (453 ms), and at a magnitude of 72 ms between the control group and the cellular telephone conversation group (464 ms). A study from Makishta and Matsunaga (2007) also suggested that the reaction time to a buzzer sound was augmented by about 350 ms when making mental calculation during driving. As such, Table 54 indicates that the effect of light intensity on the reaction time to accommodate for the younger group (i.e., an increase of 28 ms from Bright to Dark) would have a similar impact on their braking response as listening to the radio while driving, assuming that accommodation-related reaction time equated in a linear fashion to normal reaction time as studied by Consiglio, et al. (2003). As for the effect of light intensity for the middle-age group (i.e., an increase of 60 ms) and the older group (i.e., an increase of 97 ms), the decrease of light intensity from the bright level to the dark one may be more dangerous than the use of a cellular telephone, in terms of their reaction time in a braking response. Considering the possibility that a braking response may be triggered by the knowledge of warning signs on the dashboard, the influence of light intensity on dynamic accommodation as suggested in Table 54 (i.e., not only the change of RAT but the change of MOA, RTI, ATI, PV, and Time% as well) is certainly valuable to the practical improvement of driving safety. Hence, the first design guideline for visual signal design relates to the effect of light intensity found in the study, that is:

Design Guideline 1: The increase of signal intensity can be used to improve one's dynamic accommodative performance. Specifically, the use of 100 cd/m^2, instead of 20 cd/m^2, can shorten one's accommodation time (in terms of ATI) by about 60 ms, which is similar to the effect of avoiding using a cell phone on reaction time in a braking response.

In spite that the effect of light chromaticity did not change one's accommodation as much as the effect of light intensity (Table 54), its effect on RAT, RTI, and ATI for the younger and middle-aged groups may still be of practical usage. As such, the second design guideline regards the use of different light chromaticities as a supplementary technique to improve accommodation, that is:

Design Guideline 2: The use of a signal containing more middle-to-long wavelength light (e.g., a reddish color) can help enhance one's dynamic accommodative performance, especially for younger and middle-aged adults. Specifically, the use of the chromaticity similar to that of the red image may reduce one's accommodation time (in terms of ATI) by about 50 ms for the younger and middle-aged groups, which is similar to the effect of avoiding using a cell phone on reaction time in a braking response.

As for the older group, Table 54 suggested that compared with the other two groups, the increase of light intensity or the use of the red image did not improve their performance remarkably for almost every aspect of dynamic accommodation. As a result, the third design guideline focuses on the aging population, that is:

Design Guideline 3: Due to the age-related accommodation loss, a signal of high light intensity and reddish chromaticity should always be used along with other techniques so as to create a suitable stimulus for older adults to accommodate. Other techniques may include enlarging target size, avoiding locating targets in short distances, and utilizing simple signals that do not require fine focus.

In summary, based on the findings of the study, different light intensities and chromaticities may have different impacts on the age-related dynamic accommodative performance. Accordingly, three design guidelines for visual signal design were proposed. It must be noted, however, that since visual perception and users' satisfaction is not determined solely by good accommodative performance, the final decision on signal selection or display design must be made with the consideration of many other important factors such as personal preferences, information perception, safety, cost, and technical feasibility. For example, while the participants accommodated the red target better than the blue target, the use of the red color may also convey a sense of emergency or criticality to a person (Gao, et al., 2007). As a result, designers must consider whether it is worthwhile using the red color under certain situations to enhance one's accommodative ability when other color-related effects exist.

6. Conclusion

6.1 Uniqueness of the study

The present study aimed to elucidate the effects of aging, light intensity, and chromaticity on the dynamic accommodative ability of the eye as well as their interactions. The results of the study not only supported the use of the modified autorefractor to investigate the dynamic accommodative characteristics for adults under various lighting conditions, but also provided better insight into the effects of aging and different lighting conditions on the dynamic accommodative ability of the eye. The advancing of age was found to have a profound impact on one's dynamic accommodative performance, including decreased magnitude of accommodation (also found in peer research: Ramsdale and Charman, 1989, Koretz, et al., 1989, Glasser and Campbell, 1998, Mordi and Ciuffreda, 1998), prolonged reaction, response, and total accommodation time (also found in peer research: Sun, et al., 1988, Ciuffreda, et al., 2000, Heron, et al., 2002), and reduced peak velocity as well as the percentage of the response time to reach that velocity. Similar phenomena were observed when the intensity of light was reduced or the target was switched from red to blue (Johnson, 1976, Rosenfield, 1993, Arumi et al., 1997, Jackson, et al., 1999, Kroger and Binder, 2000).

The uniqueness of the study is embedded throughout the design of the experiment, the analysis of the data, and the implications of the results.

1. The current study is the first to investigate both the effect of aging and the effect of light (its intensity and chromaticity) on one's dynamic accommodative performance utilizing the modified autorefractor. With the consideration of both the internal factor (the aging of the eye) and the external factor (different lighting conditions), a more comprehensive knowledge of the mechanism of accommodation was achieved (see Section 5.2 A biomechanical and neural model of an accommodation process).

2. In order to measure accommodation, a mirror machine system (Figure 8) was designed to create an abrupt change of targets at different distances. The system provides a track to position targets of different characteristics at different distances or to move them along the track. Additionally, as the autorefractor has an internal camera to capture the image of the eye, it has the potential to not only measure accommodation but also assess the movement of the eye. As a result, researchers may utilize this setup for a variety of purposes (e.g. far-to-near/near-to-far accommodation, dark focus, vergence accommodation, and saccade).
3. Unlike other studies investigating dynamic accommodation, a replicable and mathematical data processing technique was developed in the present study. Utilizing Savitzky-Golay filtering, high frequency noise can be easily removed from the raw data, resulting in a clear accommodation response. After converting the smoothed accommodation response to a velocity curve, the onset and offset of accommodation can be uniquely identified, which eliminates the use of subjective visual detection and enables comparison of results across studies.
4. To parameterize a dynamic accommodation response, the study presented six parameters. Although the magnitude of accommodation (MOA) and reaction time (RAT) have been observed previously (Sun, et al., 1988, Ciuffreda, et al., 2000, and Heron, et al., 2002), the response time index (RTI), the accommodation time index (ATI), the peak velocity (PV), and the percentage of time to reach its peak (Time%) were created based on the recorded accommodation responses. As discussed in Section 5.3, The choice of MOA, RAT, RTI, ATI, PV, and Time%, the six parameters work together to provide a comprehensive view of the dynamic accommodative characteristics.
5. Based on the findings of the study, a biomechanical and neural model was developed (Figure 67), which connected the current knowledge of accommodation-related neurons and the physiological structure of the eye into one model. Most importantly, the model illustrates how the three independent variables (age group, light intensity, and light chromaticity) and the six dependent variables (MOA, RAT, RTI, ATI, PV, and Time%) are involved in an accommodation process.

6. Last but not least, the design guidelines for visual signal design were based on the actual findings of the study (Table 54). Although it is plausible that the increase of light intensity or the use of reddish images may improve one's accommodation, the design guidelines provide information about how accommodation can be improved in the dynamic domain. That is, the guidelines can help designers understand the importance and significance behind the change of accommodation time (by milliseconds) under different lighting conditions.

To summarize, the current study focused on investigating the basis of the accommodation process of the eye. With the development of the measure of dynamic accommodation, the age-related accommodation loss was elucidated under different lighting conditions.

Within the experimental design space of the study, the author believes that the findings of the study can provide better insight into the dynamic accommodative ability associated with aging, light intensity, and light chromaticity, which may be applied to automotive products design, medicine and biology, and driver's screening test. For example, the intensity and chromaticity of signals in the instrument cluster may be designed based on Design Guidelines 1 & 2. Additionally, non-visual clues (e.g., auditory signals, Lockhart and Casali, 2004) may be incorporated in the instrument cluster as well to further facilitate the information perception of aging drivers. On the other hand, as Virtual Reality has been used increasingly in medicine and biology (e.g., 3D models of human anatomy, Camp, et al., 1998), the VR images may be displayed according to the proposed guidelines so as to help viewers better perceive the images. Another implication regards the measure of dynamic accommodation as a screening test for driver's vision. Since the age-related accommodation loss (especially, the dynamic aspects as found in the present study) may increase driving risk (e.g., reduced visual attention and increased reaction time to brake), the measure of dynamic accommodation developed in this study may help identify at-risk drivers by assessing their dynamic accommodative ability.

6.2 Limitations of the study

In spite of the findings, the accommodation process investigated was limited in a simulated environment where a driver reads information from the dashboard while driving – in other words, far to near accommodation. During far to near accommodation, innervation to the ciliary muscle is increased from some initial level to increase the refractive power of the lens. On the contrary, during near to far accommodation, innervation to the ciliary muscle is lowered to reduce the refractive power of the lens. As a consequence, it would be of value to study the dynamic near to far accommodation and compare the results with those from the present study, which could expand our knowledge of the nature of an accommodation process.

Additionally, the study was confined to an abrupt change of the stimulus for accommodation and the exclusion of vergence-related accommodation. As the modified autorefractor was shown to be capable of capturing accommodative status for sinusoidally changed stimulus (Wolffsohn, et al., 2001), the study of dynamic accommodation with a continuous stimulus would help evaluate the effects of eye fatigue on accommodation. On the other hand, since the study assured the alignment of the tested eye with the center of the far and near targets, vergence of the eyes was eliminated from the study. In other words, the experiment 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 may provide us with a more comprehensive understanding of accommodation, as it takes into consideration the actual movement of the eye, the saccade.

Furthermore, with the advancing of the autorefractor technique, a more reliable, faster, and easier measure of accommodation may become available, which would better facilitate the study of dynamic accommodation. In the current study, due to the nature of the autorefractor used, the participant must pass the screening test to ensure that he or she had normal vision. Corrected vision was accepted only if the participant wore contact lenses. As a result, this study was limited to those having relatively healthy eyes and with no visual deficits. In this sense, the findings of the study might represent only a portion of the US population who do not have vision problems. However, since vision problems become prevalent when people get older (Shinar and Schieber, 1991), it would be of value to understand the accommodative performance of this population. Such studies may become feasible in the near future with the release of new and more powerful autorefractors.

6.3 Recommendations and future research

The present study investigated the age-related accommodative performance under different conditions of light intensity and chromaticity. Based on the results, three design guidelines were proposed for visual signal design. As only two levels of light intensity and two levels of light chromaticity were assessed, future study must expand the guidelines with the inclusion of more lighting conditions. That is, by testing more intensities other than 100 cd/m^2 and 20 cd/m^2 and more chromaticities other than red and blue, the results can help discover how the dynamic accommodative characteristics change for each unit level of light intensity or chromaticity. If so, a more detailed guideline may be available to help designers select an exact level of light intensity and chromaticity based on their own needs.

In addition, future research may also explore the effect of eye fatigue on dynamic accommodation. As the current study provided the participants with plenty of rest between measures, it was assumed that each participant returned to their initial status before each measure. In daily life, however, an accommodation process may happen following a variety of circumstances which may trigger eye fatigue (e.g., reading a book, looking at a computer screen, and exposing to high-beam light). Hence, it would be intriguing to evaluate how fatigue influences the dynamic accommodative performance, especially for people at older ages. If the study does suggest that the fatigue of the eye results in changes of the dynamic accommodative performance, further investigation may be conducted to assess how long it may take the eye to recover from fatigue and return to normal performances as found in the present study.

Furthermore, in order to assess near to far accommodation, one of the useful paradigms for future study is to explore the accommodative characteristics when a driver accommodates from looking at the dashboard to reading distant targets (e.g., road signs and nearby traffic). For this purpose, effort should be made to discover proper realistic targets or a certain level of light intensity and chromaticity so as to simulate real-world driving conditions.

Another recommendation regards the biomechanical and neural model as a theoretical model that requires verification. While this model can help explain the effects of aging, light intensity, and light chromaticity on accommodation found in the study, it is arguable that this model covers all of the factors that may contribute to an accommodation process. Besides, as the relationship between cones and the advancing of age, as well as the age-related changes of the accommodation plant and the neurons, was not measured directly in the study, the model cannot be quantified by the results of the study. In other words, future study should further explore the model so as to determine a loading factor for each of the links, especially, how the aging of the eye actually makes an influence on each part of an accommodation process.

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APPENDIX: Consent Form and Questionnaire

IRB Approval Letters # 06-603 (Original one and Continuation, same consent form used)

VirginiaTech

Office of Research Compliance
Institutional Review Board
1880 Pratt Drive (0497)
Blacksburg, Virginia 24061
540/231-4991 Fax: 540/231-0959
E-mail: moored@vt.edu
www.irb.vt.edu
FWA00000572(expires 7/20/07)
IRB # is IRB00000667.

DATE: October 20, 2006

MEMORANDUM

TO: Thurmon E. Lockhart
Wen Shi

Approval date: 10/20/2006
Continuing Review Due Date:10/5/2007
Expiration Date: 10/19/2007

FROM: David M. Moore

SUBJECT: **IRB Expedited Approval:** "Assessing the Visual Characteristics of Aging Individuals Via the Autorefractor" , IRB # 06-603

This memo is regarding the above-mentioned protocol. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. As Chair of the Virginia Tech Institutional Review Board, I have granted approval to the study for a period of 12 months, effective October 20, 2006.

As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in previously approved human subject research activities to the IRB, including changes to your study forms, procedures and investigators, regardless of how minor. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.
2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.
3. Report promptly to the IRB of the study's closing (i.e., data collecting and data analysis complete at Virginia Tech). If the study is to continue past the expiration date (listed above), investigators must submit a request for continuing review prior to the continuing review due date (listed above). It is the researcher's responsibility to obtained re-approval from the IRB before the study's expiration date.
4. If re-approval is not obtained (unless the study has been reported to the IRB as closed) prior to the expiration date, all activities involving human subjects and data analysis must cease immediately, except where necessary to eliminate apparent immediate hazards to the subjects.

Important:
If you are conducting **federally funded non-exempt research**, this approval letter must state that the IRB has compared the OSP grant application and IRB application and found the documents to be consistent. Otherwise, this approval letter is invalid for OSP to release funds. Visit our website at http://www.irb.vt.edu/pages/newstudy.htm#OSP for further information.

cc: File
T. Coalson 0118

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VIRGINIA POLYTECHNIC INSTITUTE UNIVERSITY AND STATE UNIVERSITY

An equal opportunity, affirmative action institution

VirginiaTech

Office of Research Compliance
Institutional Review Board
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, Virginia 24061
540/231-4991 Fax 540/231-0959
e-mail moored@vt.edu
www.irb.vt.edu
FWA00000572(expires 1/20/2010)
IRB # is IRB00000667

DATE: September 20, 2007

MEMORANDUM

TO: Thurmon E. Lockhart
Wen Shi

Approval date: 10/20/2007
Continuing Review Due Date:10/5/2008
Expiration Date: 10/19/2008

FROM: David M. Moore

SUBJECT: **IRB Expedited Continuation 1:** "Assessing the Visual Characteristics of Aging Individuals Via the Autorefractor" , IRB # 06-603

This memo is regarding the above referenced protocol which was previously granted expedited approval by the IRB. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. Pursuant to your request, as Chair of the Virginia Tech Institutional Review Board, I have granted approval for extension of the study for a period of 12 months, effective as of October 20, 2007.

Approval of your research by the IRB provides the appropriate review as required by federal and state laws regarding human subject research. As an investigator of human subjects, your responsibilities include the following:

1. Report promptly proposed changes in previously approved human subject research activities to the IRB, including changes to your study forms, procedures and investigators, regardless of how minor. The proposed changes must not be initiated without IRB review and approval, except where necessary to eliminate apparent immediate hazards to the subjects.
2. Report promptly to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.
3. Report promptly to the IRB of the study's closing (i.e., data collecting and data analysis complete at Virginia Tech). If the study is to continue past the expiration date (listed above), investigators must submit a request for continuing review prior to the continuing review due date (listed above). It is the researcher's responsibility to obtained re-approval from the IRB before the study's expiration date.
4. If re-approval is not obtained (unless the study has been reported to the IRB as closed) prior to the expiration date, all activities involving human subjects and data analysis must cease immediately, except where necessary to eliminate apparent immediate hazards to the subjects.

cc: File
T. Coalson 0118

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VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
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Informed Consent for Participants of Investigative Projects
Grado Department of Industrial and Systems Engineering
Virginia Tech

TITLE: Assessing the visual characteristics of aging individuals via the autorefractor

PRINCIPAL INVESTIGATOR: Thurmon E. Lockhart, Ph.D.

PURPOSE

The purpose of this study is to evaluate your visual characteristics via the autorefractor during the accommodation process when your eyes focus on the near and far targets.

PROCEDURE

The test will be performed at Virginia Tech, Night Vision Laboratory. You will be asked to sit in a chair and place your forehead against a forehead rest and look straight forward onto the targets. The measure of accommodation will be performed by the experimenter and you need to focus on the targets changed by the mirror machine. The targets will be shown via a laptop screen and displayed in two colors (red and blue) and under daytime and nighttime lighting conditions (100 cd/m^2 to 1 cd/m^2).

Each test session will contain one level of target color and one level of target lighting condition. Each measure of the accommodation process will take up to 10 seconds and you will be allowed to relax your eyes after each measure and take a break after finishing each test session.

The entire experiment will take two hours.

RISKS OF PARTICIPATION

Minor eye fatigue (similar to those encountered in regular driving).

BENEFITS and COMPENSATION

The proposed research will provide a better understanding of the visual characteristics of aging population, especially the accommodative ability. This information can be used for industry to design products to compromise the age-related accommodation loss, for example, via a certain combination of the intensity and color of light on the basis of the effects of light intensity and light color to be studied in the proposed research. The benefits to the subjects are better understanding of their ability to accommodate. Additionally, monetary compensation will be provided ($10.00 per hour).

ANOYNMITY AND CONFIDENTIALITY

The data from this study will be kept strictly confidential. No data will be released to anyone but the principal investigator and graduate students involved in the project without written consent of the subject. Data will be identified by subject number.

FREEDOM TO WITHDRAW

You are free to withdraw at any time from the study for any reason. Circumstances may come up that the researcher will determine that you should not continue as a subject in the study. For example, an illness could be a reason to have the researchers stop your participation in the study.

APPROVAL OF RESEARCH

This research has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Tech, and by the Grado Department of Industrial and Systems Engineering. You will receive a copy of this form to take with you.

SUBJECT PERMISSION

I have read the informed consent and fully understand the procedures and conditions of the project. I have had all my questions answered, and I hereby give my voluntary consent to be a participant in this research study. I agree to abide by the rules of the project. I understand that I may withdraw from the study at any time.

If I have questions, I will contact:
Principal Investigator: Thurmon E. Lockhart, Associate Professor, Grado Department of Industrial and Systems Engineering, 231-9088.
Chairman, Institutional Review Board for Research Involving Human Subjects: David Moore, 231-4991.

Signature of Subject ____ Date:

Signature of Project Director or his Authorized Representative:
____ Date:

Signature of Witness to Oral Presentation:
____ Date:

Questionnaire

Personal Data and Medical History
Virginia Tech, ISE Department

Assessing the visual characteristics of aging individuals via the autorefractor

Date _____________

Participant ID: ______________________________ Age _____________

Sex __________ Height (ft in) _____________ Weight (lb) _____________

1. Do you have a valid driver's license? Yes________ No________
2. How long have you had your driver's license? ____________________________
3. How often do you drive each week? _____________________________________
4. What type of vehicle do you currently drive? ______________________________
5. Have you been involved in any accidents within the past 2 years? If so, please explain (e.g., number of accidents, what type).
   ____
6. Do you drive during the night? Yes _________ No __________ If no, please explain ____
7. If you do drive at night, how often do you drive at night?
   Every day_______ At least twice a week ________Less than twice a week_______
8. Do you drive in an area that does or does not have overhead lighting at night?
   Please explain ____
   ____
9. Do you have normal or corrected normal vision? If no, please explain.
   ____
10. Do you wear bifocal or trifocal glasses? Yes________ No________
11. Did you have IOL implanted? Yes__________ No ___________________

Check if susceptible to:

Shortness of breath _____ Dizziness _____ Headaches _____
Fatigue _____ Pain in arm, shoulder or chest ______

If you checked any of the items above, please explain ___________________________

Are you currently taking any type of medication? ______ If so, please explain:
____

Have you had or do you now have any problems with your blood pressure? _______

If so, please explain: ____

VITA

Wen Shi

2175 Hammes Street, Christiansburg, VA 24073
(540) 557-7884
wenshi@vt.edu

OBJECTIVE

Position in Human Factors Research, especially in the field of human factors research & analysis, transportation safety, driver research, HMI design & evaluation, and usability study.

EDUCATION & AWARD

Ph.D. Candidate, Industrial & Systems Engineering, Planned Graduation: Fall, 2007
M.S., Industrial & Systems Engineering, December 2005, GPA 3.8/4.0
Both from the Human Factors Engineering & Ergonomics Program at the Grado Department of Industrial and Systems Engineering, Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA
B.S., Industrial Engineering, May 2004, Department of Industrial Engineering, Tsinghua Univ., China
UPS Doctoral Fellowship, 2006-07

RESEARCH PROJECTS

Automotive Interior Design via the Cognitive/Behavioral Characteristics of US Drivers
-- **Co-Principal Investigator**; Duration: Fall 07; sponsored by Hyundai Motor America, USA
-- Designs interior interface, conducts experiment, analyzes data, and publishes results

Driver's Visual & Physical Capabilities and Their Naturalistic Driving Performance
-- **Project Leader**; Duration: Fall 06 - Fall 07; sponsored by Virginia Tech Transportation Institute
-- Designs a test battery, conducts experiment, analyzes data, and publishes results

Interior/Exterior-use Anti-glare Items and Their Effects on Automotive Safety
-- **Project Leader**; Duration: June 05 - March 06; sponsored by TOYOTA Motor Co., Japan
-- Designed & conducted experiment, analyzed data, and published results

Effects of Tinted Glass Articles on Vehicle Occupant's Vision, Comfort, and Safety
-- **Project Leader**; Duration: Spring 05; sponsored by PPG Industries, Inc., USA
-- Designed & conducted experiment, analyzed data, and published a journal paper

In-vehicle Information Display Design & Its Effects on US Drivers' Vision and Safety
-- Duration: June 04 - March 05; sponsored by TOYOTA Motor Co., Japan
-- Designed display terminal, conducted experiment, analyzed data, and published results

User Needs Assessment and User-centered Design of Mobile Phone Interface
-- Duration: Fall 04; sponsored by TOSHIBA Co., Japan
-- Designed mobile phone interface, conducted surveys and interviews, and analyzed data

PUBLICATION

Dissertation (2007): Investigating the Dynamic Accommodative Performance of Drivers at Different Ages and Designing & Prototyping In-vehicle Applications to Enhance Driving Safety
Bachelor's Thesis (2004): Usability Study & Design of Online Banking Systems in China
(1) Shi, W., Lockhart, T.E., and Arbad, M. (In Press, Peer Reviewed, Journal of Safety Science) Tinted Windshield and its Effects on Aging Drivers' Visual Acuity and Glare Response
(2) Shi, W., and Lockhart, T.E. (2007). Temporal Accommodative Characteristics of the Eye Associated with Aging and Target Light. In *Proceedings of HFES 2007 Conference*, Baltimore, October 2007
(3) Shi, W., Lockhart, T.E., and Atsumi, B. (2007). Dynamic Accommodative Performance on Dashboard Reading for Aging Drivers in the US. In *Proceedings of JSAE 2007 Congress*, Kyoto, Japan, October 2007
(4) Lockhart, T.E., and Shi, W. (2006). Final Report for the 2005-06 TOYOTA Co. Project
(5) Lockhart, T.E., and Shi, W. (2005). Final Report for the 2005 PPG Inc. Project

SKILLS

Computer: SAS, LabVIEW, MS Office, Visio, Flash, Photoshop, AutoCAD, MATLAB, JMP, C
Language: Written and oral fluency in Chinese (Mandarin) and Japanese (Certified)