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ACCOMMODATION – CLINICAL AND THEORETICAL INVESTIGATIONS

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ABSTRACT

Background: Accommodative insufficiency (AI) is a relatively common visual anomaly in children and young adults with an estimated prevalence of about 5%. Patients with AI usually suffer from blur, headaches and asthenopia associated with near work. The two most important treatment regimes for AI are plus lens reading additions (PLRA) and orthoptic exercises with the aim of normalising the accommodative system. The stimulus for the accommodative system is blur, which is an even-error signal, i.e., the blur gives the magnitude of the accommodation, but lacks the directional information; therefore, it is dependent on other cues to know if the accommodation needs to be increased or reduced. The main directional cues for the accommodative system are thought to be chromatic aberration (CA) and spherical aberration (SA). Recently there has been a large interest in the use of contact lenses to correct aberrations in order to create an improved image quality or create a near addition.

Aims: The purpose was to evaluate the outcome of AI treatment, to investigate the effect on accommodation response when manipulating the directional cues to accommodation and to study the effect on accommodation when using a multifocal contact lens.

Material and Methods: 46 children between 7-18 years of age, diagnosed with AI were dissipating in study I and II where they were treated with PLRA (+1.00 or +2.00D) or orthoptic exercise. In study III and IV, a normal group of 40 subjects were included (age 21 to 35) and 5 AI patients (age 10 to 18). They had their aberration and accommodation measured with and without accommodative cues present, and also with a multifocal contact lens which gives a near reading addition.

Results: The result showed that there was no significant difference between the two treatment methods for AI patients. Further, there was a significant difference between the PLRA given, which indicates that the PLRA should not be of the higher strength. The accommodative response was not affected when the accommodative cues was eliminated or decreased. The multifocal contact lens was not able to relax the accommodation in young normal subjects and neither on AI subjects.

Discussion: Results of our study and others have shown that vision therapy (PLRA and/or orthoptic exercises) can improve the time characteristic and magnitude of accommodation response with a persistent result. The PLRA of +1.00D is preferred to allow comfortable vision at near and at the same time exercise and stimulated the accommodative system rather than completely relieved. The SA and CA were showed to not be a strong directional cue for the accommodation which indicates that there are other cues more important for directional information. Since the multifocal contact lens was not able to relax the accommodation for neither of the subjects it is therefore unlikely that subjects with AI can be effectively treated with such lens.

Conclusion: Based of the finding in the studies I would like to recommend that AI subjects can be treated with either +1.00D reading addition or orthoptic exercise, however, multifocal contact lenses should not be used for the treatment purpose of AI subjects.

Keywords: Accommodative insufficiency, Plus lens reading addition, Spherical flipper treatment, Spherical and Chromatic aberration, Spherical aberration controlled contact lens.

LIST OF PUBLICATIONS

I. Brautaset, R. Wahlberg, M. Abdi, S. Pansell, T. Accommodation insufficiency in children: are exercises better than reading glasses? *Strabismus*. 2008; 16:65-69.

II. Wahlberg, M. Abdi, S. Brautaset, R. Treatment of accommodative insufficiency with plus lens reading addition: is +1.00 D better than +2.00 D? *Strabismus*. 2010; 18:76-71.

III Wahlberg, M. Lindskoog Pettersson, A. Rosén, R. Nilsson, M. Brautaset, R. Clinical importance of spherical and chromatic aberration on the accommodative response in contact lens wear. *Journal of Modern Optics*. (First published on: 21 march 2011 (iFirst))

IV Lindskoog Pettersson, A. Wahlberg Ramsay, M. Lundström, L. Rosén, R. Nilsson, M. Unsbo, P. Brautaset, R. Accommodation in young adults wearing aspherical multifocal soft contact lenses. (Manuscript).

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LIST OF ABBREVIATIONS

AI	Accommodative Insufficiency
AC/A	Accommodative Convergence/Accommodation
CA	Chromatic Aberration
CA/C	Convergence Accommodation/Convergence
cpm	cycles per minute
D	Dioptre
HOA	Higher Order Aberration
LOA	Lower Order Aberration
MEM	Monocular Estimated Method
NRA	Negative Relative Accommodation
PLRA	Plus Lens Reading Addition
PRA	Positive Relative Accommodation
RAF	Royal Air Force
RMS	Root-Means-Square
SA	Spherical Aberration
SACL	Spherical Aberration Controlled Contact Lens
TFC	Trial Frame Correction
UC	Uncorrected
VAS	Visual Analogue Scale

1 INTRODUCTION

A blurred retinal image will stimulate the visual system and in response the intraocular lens will change its shape and alter the dioptric power of the eye. This change in dioptric power of the eye is called accommodation and it enables objects placed from far point to near point of the eye to be viewed clearly. Without accommodation, all objects closer than the far point would be blurred, and near task performance would significantly decrease. Accommodation is part of a complex triad which is called the near response or the near reflex. When the fixation is moved to an object at near distance, a near synkinesis is evoked that includes increased accommodation, convergence and pupillary constriction. If the object moves away from the subject, the opposite will occur.

Today it is not uncommon that many spend most of their day doing near work. Among workers, one of the most common near visual tasks is computer work or looking at other types of electronic displays. Computer work is common among children and young adults, but also to spend a lot of the time doing other near visual tasks such as reading and writing. Looking back to 1980, only a small percent of the people were using a computer for their daily work activities, but nowadays the computer is commonly used in work and for personal use at home. To attain the optimal level of comfortable vision, the accommodation and vergence systems must work properly. Accommodation is quite flexible and resistant to fatigue; despite this, accommodative dysfunction is a relatively common visual anomaly in children and young adults. The capability to accommodate decreases whit age, a process called presbyopia. Somewhere between 50 and 60 years of age, presbyopia renders the eye unable to change its power. The mechanism of accommodation has interested scientists for several hundred years, back to the times of Kepler (1571-1630) who established the modern terms “principles of dioptrics”, Porterfield who in 1738 gave the focusing ability of the eye the name “accommodation”, and Young who in 1801 finally described the mechanism that changes in shape of the lens (for reference see Howard, 2002). However, even today the mechanisms of accommodation, its dysfunction and presbyopia are not fully understood.

1.1 PHYSIOLOGY AND NEURAL ANATOMY OF ACCOMMODATION

1.1.1 Physiology of Accommodation

Accommodation is a complex function that involves the crystalline lens, zonule fibres and the ciliary muscle. The crystalline lens is a biconvex transparent structure; the convexity of its anterior surface is less then the posterior surface of an un-accommodated eye. When accommodation occurs, the anterior surface of the lens becomes steeper which increases the refractive power of the eye. Structurally, the lens is divided into the capsule, an elastic envelope capable of moulding the lens substance during accommodation, and the lens substance which is made of fibres and other interstitial material. It is suspended in the eye by zonule fibres that are inserted into the equatorial region of the lens capsule. The zonule fibres originate in the ciliary body and transmit the contraction of the ciliary muscle to the lens capsule. The zonule fibres can be relaxed or straight depending whether the ciliary muscle contracts or relaxes. When the zonule fibres relax, the lens gets thicker and will accommodate; when they straighten, the eye is unaccommodate (Hart, 1992). A schematic illustration can be seen in figure 1. Although the lens, ciliary body and zonule fibres are involved in accommodation, it is the ciliary muscle that is the active element while the others occur in a passive manner. When the ciliary muscle contracts, it pulls the ciliary body forward and inward i.e., the ring formed by the inner apex of the muscle narrows, the anterior zonule is then relaxed allowing the elasticitet of both the lens and lens capsule to work appropriately (Ciuffreda, 1998).

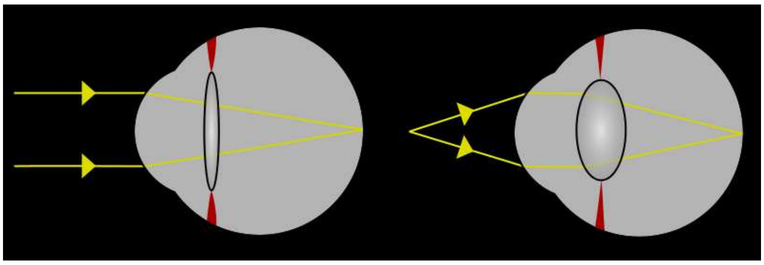

Figure 1. This is a simplified picture illustrated the unaccommodated eye (left) and the accommodated eye (right). Normally will the light rays also refract in the crystalline lens, which the unaccommodated eye (left) is missing.

The ability to accommodate slowly decreases throughout life (Duane, 1912), the exact age at which this occurs for any individual depends, e.g., on the ametropic state and working distance etc (Atchison, 1995a). The near point of accommodation recedes toward the far point, so that small objects must be held further and further from the eye to be clearly visualized. This phenomenon has nothing to do with ocular pathology and is called presbyopia (physiologic loss of accommodation in advance age). Presbyopia will affect 100% of the population over 50 years of age (Weale, 2003). Studies of accommodation measured subjectively indicate that 1 to 1.5 dioptre (D) remains even after 65 years of age, although this residual probably does not represent “active” accommodation (Hart, 1992). Most of it probably represents depth of field and depth of focus of both the optical system and retinal elements. The development of presbyopia is not well understood, and there are many theories and hypotheses which attempt to explain its mechanisms. One of the major theories suggests that presbyopia results from a hardening of the crystalline lens (Atchison, 1995a; Heys et al., 2004; Weeber et al., 2005). There are also other theories, for review see Atchison (1995a).

1.1.2 Neural Anatomy of Accommodation

The visual system is the most complex of all the sensory systems. A comprehensive evaluation of neurological visual functions, including accommodation, should therefore be part of a standard eye examination. Deficiencies of accommodation can be associated with poor academic performance, but can also signify a neurological or systemic abnormality (Braun et al., 1995; Ohtsuka et al., 2002). Contraction of the ciliary muscle is stimulated by the parasympathetic fibres of the oculomotor nerve III arising in the mid brain. The resting state of accommodation (also termed tonic accommodation) seems to be due to a balance of resting sympathetic and parasympathetic tone to the ciliary muscle, with the latter being predominant (Hart, 1992). Whether the sympathetic fibres play any role in accommodation has been discussed, for a review see Gilmartin (1986). A hypothesis of the sympathetic innervation has been postulated due to the finding of that the ciliary body contains beta-adrenergic sympathetic receptors (Gilmartin, 1986).

The afferent pathway that stimulates accommodation and the direct and consensual light reflex starts in the retinal receptors and then continues through the optic nerve, optic chiasm, optic tract, the pretectal nucleus and to the Edinger-Westphal nucleus which generates accommodation and miosis. The sensory stimulus to accommodation is a blurred retinal image and the impulse reaches both the Edinger-Westphal nuclei (which is the parasympathetic nucleus of the oculomotor nerve) and travels through the oculomotor nerve to the ciliary ganglion in the orbit. The majority of the postganglionic parasympathetic fibres enters the globe through the short ciliary nerves, and some postganglionic fibres travel with the long ciliary nerves, and innervate the iris sphincter and the ciliary muscle to cause miosis and accommodation (Hart, 1992) (see figure 2).

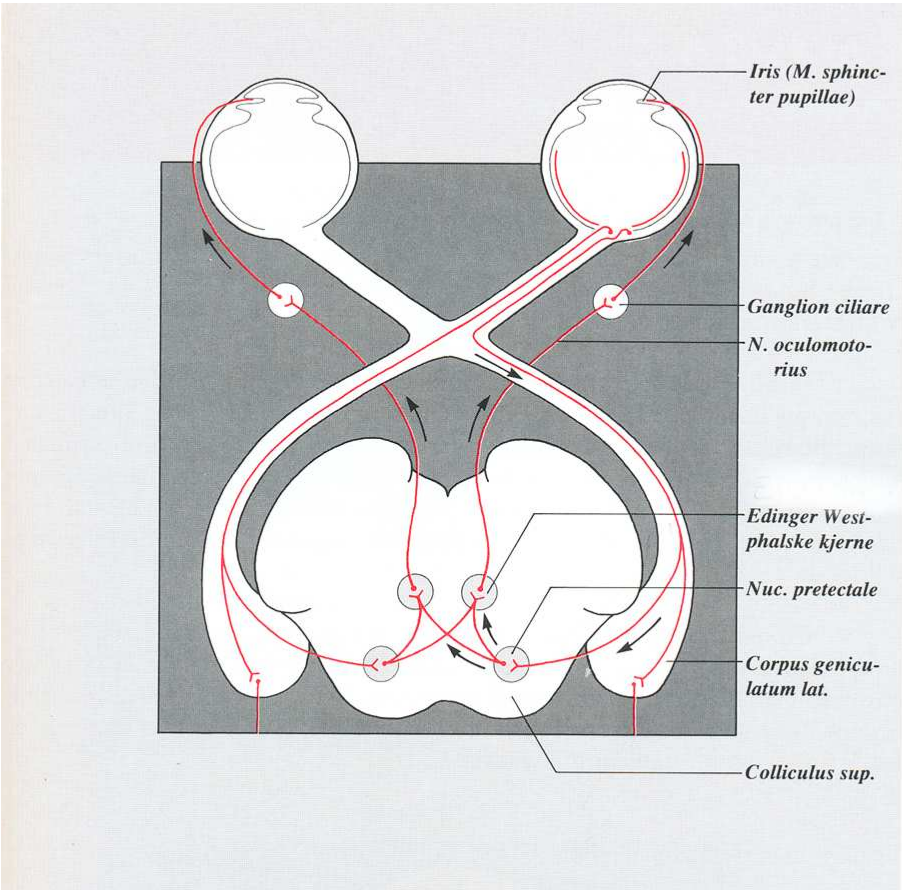

Figure 2. Illustration of the neural pathways involved in the light reflex and accommodation. Picture printed under permission from the publisher (Tell Forlag).

1.2 MODELLING ACCOMMODATION AND VERGENCE

1.2.1 The Accommodative System

In 1956 Heath developed a classification for accommodation in which he divided accommodation into functional or operational units (similar to Maddox´s components of vergence, 1893). This formed a conceptual structure for the relationship between the accommodative stimulus, its separate and interactive motor effects, and the final overall steady-state system response. Heath (1956) included the following components:

- *Reflex accommodation* – the automatic adjustment of refractive state to maintain a clear and focused retinal image in response to blur input. This occurs for blur up to approximately 2.00D (Fincham, 1951, 1953; Ciuffreda, 1991). Beyond that, the voluntary accommodation effort is required (Fincham, 1951, 1953). Reflex accommodation is the dominate and most important component of accommodation; in the role that generate the steady state response under both monocular and binocular conditions (Hung et al., 1996).
- *Tonic accommodation* – present when there is no input of blur, disparity, and proximity input. It is due to a balance between the resting sympathetic and parasympathetic tone (Hart, 1992). The tonic accommodation amount varies among individuals with a mean value of approximately 1.5D (0.7 SD) (Gilmartin, 1986).
- *Proximal accommodation* – accommodation due to the knowledge of nearness of an object. Under normal viewing conditions, i.e., closed-loop, proximal accommodation has a small contribution to the total response (Hung et al., 1996).
- *Convergence Accommodation* – accommodative response that occurs solely due to changes in the vergence system. Convergence accommodation is the second largest component of accommodation (Ciuffreda, 1998).

Most biological systems have the ability to adapt to changing conditions in the environment, e.g., the olfactory and auditory systems. The ability of adaptation has also been proposed in the accommodative system. Following prolonged accommodative effort, e.g., viewing a near target, the accommodation will manifest as motor after-effects that appear when the stimulus for accommodation has been removed. The accommodation will than more slowly return to its normal resting state of accommodation (tonic position). The adaptation maintains accommodation to provide comfort for the accommodative system (Miles, 1985; Rosenfield & Gilmartin, 1989).

1.2.2 The Vergence System

The eyes of an individual with normal functional binocular vision are oriented so that the visual axes of the two eyes are close to parallel when viewing a distant object. When one eye turns as compared to the other, there is vergence between the two eyes. The purpose of vergence eye movements is to put a fixation target on the horopter i.e., stimuli that fall on the corresponding retinal points, and keep it there. Similar to the accommodation system, the vergence system also consists of components which give rise to the final output (Maddox, 1886; Ciuffreda, 1998). These components are:

- *Fusional vergence* – occurs in response to retinal disparity to avoid diplopia and is reflex stimulated.
- *Tonic vergence* – the balance in the tonic innervation to the extraocular muscles determines the tonic resting state of the eyes.
- *Proximal vergence* – stimulated by any cue that elicits depth and distance perception. It initiates large vergence steps, when looking from a distant object to a near object.
- *Accommodative Convergence* – the vergence response that occurs solely due to changes in the accommodative system.

The vergence system also demonstrates adaptation. Previous studies have shown results indicating flexibility in the oculomotor system's ability to adapt to visual input such as prism; this phenomenon is called prism adaptation (Henson & North, 1980; Brautaset & Jennings, 2005, 2006; Nilsson & Brautaset, 2011).

Analogous to the accommodative system, the vergence system can also have convergence dysfunction. Vergence dysfunction can cause a variety of symptoms such as blur, diplopia, eye strain, ocular discomfort during near work, frontal headaches, decreased visual performance and a pulling sensation of the eyes, etc (Rutstein & Daum, 1998; Ciuffreda, 2002). Convergence or vergence dysfunctions will not be further discussed in this thesis.

1.2.3 A control system

Various models of the accommodative and vergence system have been used to provide a comprehensive, organizational framework for logical thinking and conceptual understanding of the elemental components. By considering individual components, it is possible to gain insight into the accommodative and vergence process. When specific system aspects are abnormal, this allows evaluation of which aspects normalize during vision therapy. The model of accommodation and vergence are developed from the bioengineer model which was developed to analyse, predict and control the behaviour of engineering control systems. The terminology used in the control system theory is useful for the understanding of accommodation and vergence systems and will be described in a system diagram, see figure 3.

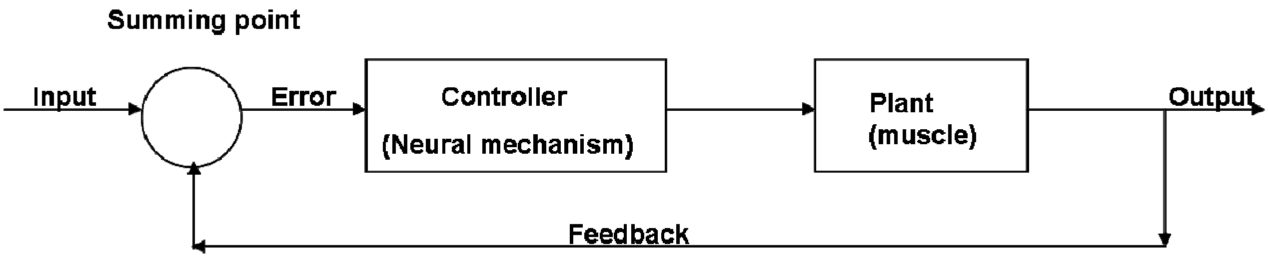

Figure 3. An illustration of a simplified control system with a negative feedback loop. The boxes represent the accommodative and vergence controller and the plant (i.e., ciliary muscle or extra ocular muscles) and the lines, the communications between the mechanisms. The circle is the summing point.

The control system of accommodation and vergence is arranged so the output is detected, fed back and subtracted from the input at the summing point i.e., a negative feedback system. This means that the error tries to eliminate itself by driving the output into alignment with the input. Any misalignment remaining is called a steady state error which represents a purposeful error necessary to sustain accommodation or vergence. The error (the line between the summing point and the controller) is the difference between in the input and the output and will stimulate the controller. The error passes through the accommodative and vergence controller (neural mechanism) which creates a neural signal and sends the outflow to the plant (ciliary muscles or extra ocular muscles) which will reduce the error. The output is dependent upon the neural outflow and the muscle itself.

1.2.4 Model of the Accommodative and Vergence System

The accommodative and vergence system has been modelled as a dual-interactive negative feedback model. Figure 5 is a simplified model from Schor (1986) illustrating mutual interactions between the accommodation and vergence system. This model will now be explained further with the focus on the accommodative system.
The accommodative and vergence system are stimulated by blur and disparity respectively i.e., the input. The input for each system has to exceed the threshold of depth of focus for the accommodative system and fixation disparity for the vergence system, which allows a small system error to be tolerated without the perception of blur or disparity. Without the neural tolerance for blur (or disparity in the vergence system), the system would be forced to have a perfect motor system response at all times. The controllers for both the accommodative and vergence systems have a fast and a slow component (Schor, 1979a, 1986). The fast component (also called reflex, phasic accommodation) is characterized by the reflex response to small amounts of blur or disparity but has a low gain. Since the gain of the fast component is low, all effort to maintain the innervation will fatigue the system. The slow component (also called tonic accommodation) has a high gain and a long time constant i.e., it reacts slowly but the capacity is large and does not fatigue easily. The slow component is regarded to be a dynamic element, and under non-sustained viewing conditions the value is zero. Further, the slow component is adaptable, i.e., adaptation is demonstrated by the continued responses (after-effects) of the motor systems when their stimuli have been removed and have not been replaced by a new stimulus. After-effects of accommodation can be stimulated directly by lenses or indirectly by vergence via vergence accommodation. The role of adaptation seems to relieve the fast accommodation and to sustain the motor response for a prolonged period, to prevent and minimize system fatigue and correlated near-work symptoms. The fast and slow components appear to respond to different stimuli. The stimuli for the fast component are blur or retinal disparity while the slow component seems to be stimulated by the output of the fast component (Schor, 1980, 1986; Jiang, 1996). The controller of both the accommodative and vergence system has been described as a leaky integrator controller (Schor 1979b, 1980; Schor & Kotulak, 1986). The leaky integrator systems create the steady state error. The steady state error is a small error that assists to maintain a given accommodation and vergence. The small error drives the fast integral controller to compensate for the leakage or the decay of accommodation or vergence. Fixation disparity is the steady state error for the vergence system whereas the lag or lead of accommodation is the steady state error for accommodative system.

The fast component are responsible for the initially accommodation and vergence response within the first second. Gradually the slower adaptable component reduces the stress on the fast system and makes it available for a rapid response to later stimuli (Schor, 1980). The slow component needs about 8-10 seconds of constant flow to take over from the fast system (Schor, 1983a). The sum of these both components is the total outflow to the muscle. The output of the fast component decays quickly, over a 10 to 15 seconds, but on the other hand, the slow system increases its output to relieve the fast system, which maintains a constant output to the muscle, see figure 4. If the slow adaptive component does not work properly the fast component has to give away a sustained output to avoid a blurred image. Fisher et al. (1987) suggested that subjects who adapt slowly would require a higher level of fast accommodation and vergence during near vision and that this may be related to the onset of asthenopic symptoms.

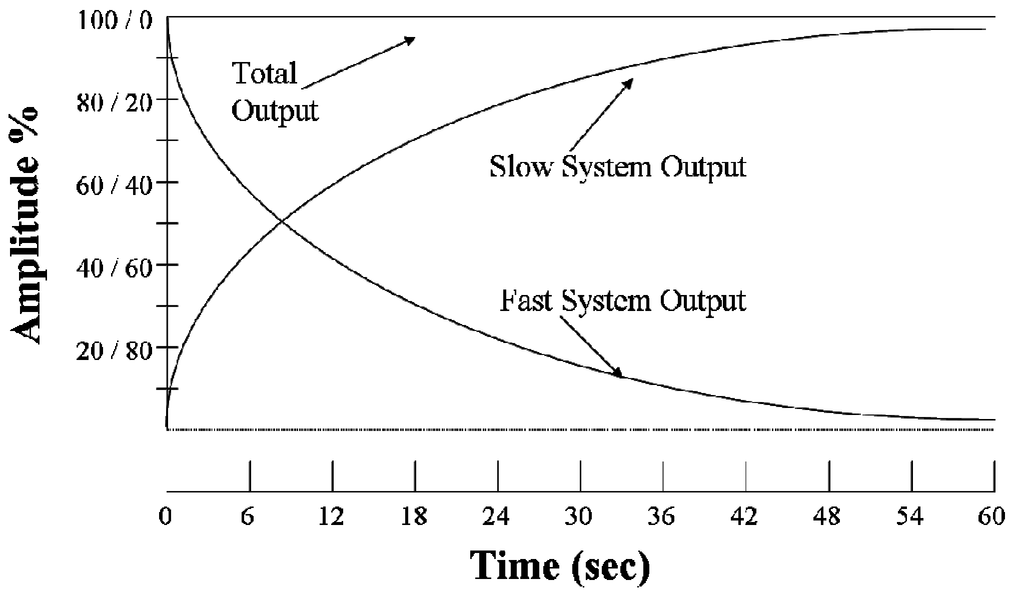

Figure 4. Illustrate a normal (asymptomatic) system of the fast and slow components. The amount of the fast component output decays as the amount of slow components output increases to keep the total output constant. The first number (e.g., 20/80) on the scale on the vertical axis indicates the amplitude of the slow system, and the second number (20/80) the amplitude of the fast system. Figure modified from Schor (1980, 1983a).

The accommodative and vergence system interact with each other through the cross link, i.e., the indirect response. The cross-link is the mutual interaction between the accommodation and vergence systems and it represents the accommodation that is created from the vergence system, i.e., the convergence accommodation/convergence (CA/C) ratio, and the vergence created from the accommodative system, the accommodative convergence/accommodation (AC/A). The cross link gains have been found to be very sensitive to parameter value variations and are responsible for producing oculomotor imbalance (Schor, 1983b; Hung & Ciuffreda, 1994; Schor, 1999). With the organization of Schor’s model (1986), the cross link interactions are directly proportional to the fast component and inversely proportional to the slow adaptive component (Schor & Kotulak, 1986; Schor & Tsuetaki, 1987). For example, the main input to the AC/A and CA/C is received from the fast accommodative and vergence components. When the slow adaptive component increases, the fast component decreases and the cross links decreased (Schor, 1986). On the other hand, Rosenfield and Gilmartin (1988) found results indicating that both the fast and slow adaptive component of the near response acts as stimuli to the cross-links. However, they base the theory on the model of Hung et al. (1996).
It has been shown that the main factor determining the amplitude of the AC/A and CA/C is the degree of adaptation of the relative slow components. For example, a low AC/A indicates that the accommodation is more adaptable and likewise, a low CA/C indicates that the vergence is more adaptable (Schor, 1986). If the AC/A ratio are abnormally high it will give a big input to the vergence system and could lead to

convergence excess, or the opposite, an abnormally low AC/A ration could give rise to a convergence insufficiency. Consequently, robust adaptation reduces both fast innervation and the input to cross-link interactions (Schor & Tsuetaki, 1987).

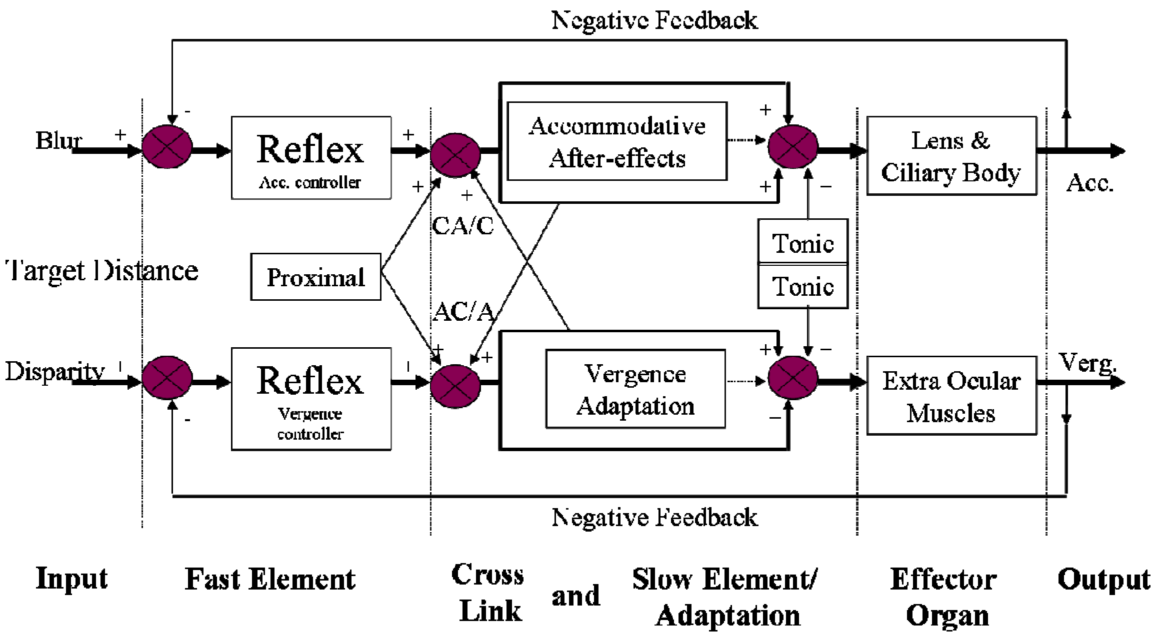

Figure 5. Illustrates a model of mutual interactions between the accommodation and vergence systems. The figure is modified from Schor (1986).

The input to the proximal branch is target distance and it merges with the input from the reflex branch into the second summing point. Under normal binocular, closed-loop (i.e., with blur and retinal disparity feedback present) viewing conditions, the proximal accommodation only adds around 4% to the final steady-state accommodative response and about 0.4% for the vergence system.
The tonic input is the neural innervation from the midbrain and has a negligible influence on the overall closed-loop near response, approximately 0.10D for the accommodative system and even less for the vergence system (0.007 meter angle (MA), 1MA= 6Δ with a 6 cm interpupillary distance) (Ciuffreda, 2002). The influence occurs in the absence of any visual feedback, e.g., in total darkness, i.e., open-loop. The summing point, which the tonic accommodation gives input to, forms the final combined signal to the cortical and subcortical centers and innervates the ciliary body for accommodation and the extra ocular muscles for vergence. These motor changes are then returned to the initial summing junction via the negative feedback loop. The cycle is repeated until an acceptably small and stable steady-state error is attained. If the error cannot be reduced the accommodative system will experience sustained blur and the vergence system would experience diplopia.

1.3 CLINICAL ACCOMMODATION MEASUREMENTS AND FINDINGS

The clinical accommodative measurements described below are based on the subjects wearing their distance refraction if needed, since it will otherwise affect the measurement. Accommodative measurements should be performed monocularly and binocularly because the vergence and accommodative system have a mutual interaction in binocular viewing. Problems in one system may attribute to problems in the other

(Schor, 1999). Parameters of accommodation that should be evaluated to determine if a clinically significant accommodative dysfunction exists or not are: accommodative amplitude, accommodative response and accommodative facility, especially in children and others who have a high near work demand or who complain of near work related symptoms (Wick & Hall, 1987). Something to keep in mind when evaluating the system is that more findings may be revealed towards the end of the day, when fatigue is more likely to occur (Rutstein & Daum, 1998).

1.3.1 Amplitude of Accommodation

The amplitude of accommodation is the maximum dioptric increase that the accommodative system can provide the eye, measured in dioptres. In mathematical terms, the amplitude of accommodation is obtained by subtracting the near-point from the far-point. The near point is the shortest distance that allows focused vision; the far point describes the farthest point that is still discernible in focus. While wearing distance refraction the far point is regarded as being infinity. The amplitude of accommodation can be measured both monocularly and binocularly. Binocular measurements are often higher by 0.30D to 0.60D (Duane, 1922).

The accommodative amplitude can be determined using the push-up method, the minus lens technique or objectively by using dynamic retinoscopy. The push-up method is the most commonly used (Rutstein & Daum, 1998). The minus lens amplitude is expected to be 1.25D to 2.00D (Kragha, 1986; Rosenfield & Cohen, 1996) less than with push-up possible because of the minification of the target when viewing through minus lenses. When measured with dynamic retinoscopy, the average is approximately 2.70D higher than with the push-up method. Since the push-up method was used to measure the accommodative amplitude in this study, only the push-up method will be described here.

1.3.1.1 Push-up Method

To measure accommodative amplitude with the push-up method, the patient views a small target, initially placed at about 40 to 50 cm from the eyes, printed in 5 to 12 N (N units – which is a specification of the print size), with one eye occluded for monocular measurements. The target size has shown to influence the perception of blur and therefore it is recommended that a small target is used for stimulus (Rosenfield & Cohen, 1995). The target is slowly brought closer to the eye; the patient is then instructed to signal the point of first sustained blur. The movement of the target is important and a movement of 0.50 D/s is preferred (Ciuffreda, 1998); too slow or fast movement can create a bias in that the patient will report that sustained blur has occurred too soon or too late. Furthermore, it is important to have a small target and sufficient illumination (not to bright to avoid abnormal pupil constriction) because it will enhance the ability to see blur. The inverse of the measured distance in meters from the near point of accommodation to the patient’s spectacle plane is the maximal amplitude of accommodation expressed in dioptres. The measurement of the amplitude of accommodation should be repeated because it is the most efficient method to observe accommodative fatigue. The ability of the accommodative mechanism to adapt to prolong near viewing has been shown to overestimate the measurement of accommodative amplitude if doing near work before measurement. However, this overestimation is not clinically relevant (Rutstein & Daum, 1998).

1.3.1.2 Normal Values for Push-up Accommodative Amplitude

In 1912, Duane presented results of the accommodative amplitude of 1000 subjects aged 8 to 70 years. The data are still used as normal values for accommodative amplitude in relation to age. By using Hofstetter's (1944) age-expected formula, which is based on Duane's table of amplitude of accommodation, it is possible to see if the amplitude is within normal values (see table 1). Many studies (such as: Daum, 1983a; Hokoda, 1985; Scheiman et al., 1996) have used the criteria that an accommodative dysfunction is suspected when the amplitude of accommodation is 2.00D below the minimum amplitude calculated using Hofstetter's formula. Hofstetter's formula should not be used for children under eight years of age because subjects below that age were not included in the study.

Expected values
Minimum amplitude = 15 – 0.25 * age in years
Expected amplitude = 18.5 – 0.3 * age in years
Maximum amplitude = 25 – 0.4 * age in years

Table 1. Expected values for amplitude of accommodation using the Hofstetter's formula (1944) based on a given age. The *= multiply. The result is given in dioptres.

1.3.2 Accommodative Response

The accommodative response is the amount of accommodation that is generated in response to a stimulus. Because of depth of focus, the accommodative response is not equal to the stimulus demand and is usually less than the accommodative stimulus. The difference between the accommodative response and stimulus is the lag or lead of accommodation. When the accommodative response is smaller than the stimulus it is called a lag, and when it is greater, a lead. Objectly, the accommodative response is normally measured with dynamic retinoscopy; the monocular estimated method (MEM) or the Nott retinoscopy, and subjectively by using the fused cross-cylinder method. Of these, the most common technique is MEM and Nott dynamic retinoscopy. Both techniques are used in this study and are therefore explained further below. The selection of technique should be chosen according to the examiner's preference (Rutstein & Daum, 1998). However, studies of these two methods have shown an advantage for the Nott technique (Cacho et al., 1999; Garcia & Cacho, 2002).
It is also possible to measure the accommodative response fully objectively by automated refractors such as the PowerRefractor or Shin-Nippon. These instruments will be explained in section 2.1.3.1 and 2.1.3.3, respectively.
Evaluation of the accommodative response is a good screening test for children suspected of latent hyperopia since they often show an extended lag. However, poor accommodative function can cause an extended lag (insufficiency or presbyopia) or a lead (spasm). Prolonged reading can cause a shift of accommodative response in the myopic direction, i.e., toward a smaller lag or lead. A study performed in college students who read for an hour at a distance of 20 cm had an increase in accommodative response of 0.30D. These changes were correlated with increased levels of visual fatigue and suggest a tendency towards spasm of the accommodative system with prolonged reading (Rutstein & Daum, 1998).

1.3.2.1 Monocular Estimation Method Technique and Nott Dynamic Retinoscopy

When using the MEM technique the target is located at the plane of the examiner's retinoscope, and the patient views it with a downward-gaze. The target should be in the 20/25 to 20/40 range and should be adequately illuminated (with a slightly dimmed room light) for the patient to see the target while still allowing the examiner to see the retinoscopy reflex. The patient looks at the target with both eyes open and the examiner neutralizes the retinoscopy reflex motion on one eye at the time. Plus lenses neutralize "with" motion (a lag of accommodation), and minus lenses neutralize "against" motion (a lead of accommodation). To minimize any effect of the lenses on accommodation, the lens should not be held in front of the eye more than about a half of a second (i.e., shorter than the latency of accommodation). A study with the aim to evaluate the MEM technique showed that MEM is a useful clinical method for determines the accommodative response (Rouse et al., 1982).

The Nott technique of dynamic retinoscopy is said to be better than the MEM since it does not involve added lenses which can contaminate the result. The patient looks at a good accommodative stimulus (approximately 20/25 to 20/40) located at a known distance in front of the patient. The lighting is arranged so that the patient can see the target and the clinician can see the retinoscopy reflex. The examiner initially holds the retinoscopy in the same plane as the target while viewing the movement of the reflex. If the reflex is "with" motion, the examiner moves away from the patient until neutrality is achieved, if the movement seen initially is "against", the opposite is done. The lag of accommodation with the Nott technique is the dioptric difference between the stimulus and the endpoint for neutrality. If the lag is large, the retinoscopy reflex is hard to see from long distance away from the patient or if there is a lead, the examiner's head tends to get in the way of the target. Despite these difficulties, the Nott technique is a quick and accurate way to determine the lag because it does not require additional lenses. It has been showed that the MEM technique had a greater lag than the Nott technique (Cacho et al., 1999; Garcia & Cacho, 2002).

1.3.2.2 Normal Values with Dynamic Retinoscopy

The normal accommodative response at 40 cm is a lag of between 0.25D and 0.75D and is similar when using MEM retinoscopy, giving the value plano to +0.75D (Rouse et al., 1984; Tassinari, 2002). Findings below or above are considered abnormal (Rouse et al., 1984; Rutstein & Daum, 1998) and may indicate an accommodative or vergence disorder. Subjects with visual discomfort have been shown to have a lag of accommodation which develops and increases over time while viewing at near distance (Tosha et al., 2009). If the stimulus is brought closer, the lag of accommodation will increase. The target letter size has been shown to have no or little influence on the accommodative response in patients with normal binocular function.

1.3.3 Accommodative facility

Accommodative facility is the ability to increase and relax accommodation and is measured with a flip lens technique, far-near subjective assessment or dynamic retinoscopy (Rutstein & Daum, 1998). The accommodative facility tests the fast component of accommodation. The most common way to measure the facility is with the flip lens technique which is described below. Measurement of accommodative facility is affected by the power of the lenses used (increased power causes decreased facility) and the size of the target (larger letters yield better facility).

1.3.3.1 Spherical flipper

Accommodative flexibility is commonly defined as the maximum frequency at which a fixation target can be focused clearly through alternating plus and minus lenses. The measurement is performed during one minute and will give the results in cycles per minute (cpm), where one cycle is clearing one set of plus and minus lenses. The alternating plus and minus lenses induce blur which drives the accommodative system. A plus lens drives the eyes to reduce its dioptric power and a minus lens to increase its dioptric power. To measure accommodative facility, the testing should be performed monocularly and the near target size should be approximately 20/30, held at 40 cm. The patient is instructed to say “clear” as soon as the letters are clear and then the lenses are flipped from one side to the other. Plus and minus 2.00D lenses are most commonly used to measure accommodative facility. Binocular accommodative facility testing can also be performed to obtain a combined measurement of accommodative and vergence ability. For binocular testing, suppression checks have been recommended. It has been found that there is a relationship between reduced accommodative facility and binocular and accommodative dysfunctions (Garcia, 2000).

1.3.3.2 Normal Flexibility Values

An appropriate criterion for accommodative facility is difficult to establish due to varied patient age and different techniques used. Hennessey et al. (1984) have shown that asthenopia is associated with poor accommodative facility. They used a failure criteria of 3 cpm or less binocularly and 6 cpm or less monocularly, and found that symptomatic subjects preformed significantly poorer than asymptomatic subjects on both monocular and binocular facility tests. Further, Hennessey et al. (1984) indicated that symptoms would be likely to be present when the subjects completed between 3 and 8 cpm binocularly, or between 6 and 11 cpm monocularly. Rouse et al. (1989) have suggested a pass/fail criteria of 1 SD below the mean found by Zeller et al. (1984), which is less than 3 cpm binocularly, and less than 6 cpm monocularly, to improve the screening reliability. The norm established for children 12 years or younger has been studied by Scheiman et al. (1988). They suggest using the failure criterion of less than 4.5 cpm monocularly for children aged 8 to 12 and below 3 cpm for children of 6 years of age. For adolescents (older than age 13) monocular facility less than 12 cpm with ±2.00D lenses are suspect. For adults older than 20 years, binocular facility less than 10 cpm with ±2.00D lenses are abnormal. Mean values for different ages are presented in table 2.

.

	Monocularly	Binocularly
Scheiman et al., 1988		
6 years	5.5 cpm	3 cpm
7 years	6.5 cpm	3.5 cpm
8 to 12 years	7 cpm	5 cpm
Rutstein & Daum, 1998		
13 years or older	11.5-17 cpm	6-10.6 cpm
20 years or older	-	10 cpm

Table 2. The mean value of the accommodative facility for different ages.

1.4 ACCOMMODATIVE DISORDERS

The normal accommodative system is quite flexible and resistant to fatigue. Despite this, accommodative dysfunction is a relatively common visual anomaly in children and young adults. When a subject presents with an accommodative dysfunction it is important to determine whether the aetiology is functional or organic (Rutstein & Daum, 1998). Organic accommodative disorders, e.g., paresis, are less common than those with functional origin. The symptoms of organic accommodative disorders are often sudden loss of accommodation in one eye and diminished amplitude. A dilated fundus examination should been done in order to rule out retinal and vitreal abnormalities. Diseases as multiple sclerosis, diabetes mellitus, and Graves' disease can cause accommodative and vergence disorders (AOA, 1998; Braun et al., 1995). Functional accommodative dysfunction does not involve the pupil and the onset is usually not precise; most conditions have existed for several months (Rutstein & Daum, 1998). The varied causes of accommodative dysfunction make it important to evaluate the accommodative function and interpret the findings in the context of the patient history and other clinical findings to reach a management plan. In this thesis only functional accommodative dysfunction, i.e., of non-organic origin, will be described and discussed.

1.4.1 Prevalence of Accommodative Dysfunction

In a prospective study, Scheiman et al. (1996) found that the most common conditions optometrists are likely to find in a pediatric population are problems with binocular vision and accommodative disorders, after refractive errors. The prevalence of accommodative dysfunction has been reported in many studies (Hokoda, 1985; Dwyer & Wick, 1995; Scheiman et al., 1996; Lara et al., 2001), showing different results. A possible reason of the different results could be due to the different inclusion criteria's, or the difference in age. Hokoda (1985) had an older mean age than the Scheiman et al. (1996) and Dwyer and Wick (1995), where a higher demand of near work could be suspected (Scheiman & Rouse, 1994). The accommodative dysfunction not associated with the process of presbyopia probably affects at least 2-3% of the population (Rutstein & Daum, 1998). However, Hokoda (1985) found that the prevalence of symptomatic accommodative dysfunction was 16.8% in a general clinical population. Other study found that the prevalence was slightly lower around 9.4% (Lara et al., 2001). Scheiman et al. (1996) showed that the prevalence of accommodative and binocular vision dysfunction was 9.7 times greater than the prevalence of ocular disease in children between 6 months to 5 years of age and 8.5 times greater than the prevalence of ocular disease in children between 6 to 18 years of age. They also showed that accommodative dysfunction was significantly more prevalent in school-aged children (6.5%) than preschool children (1.0%). It has also been found that the prevalence of accommodative and binocular dysfunction increases when it is associated with a significant refractive error (Dwyer & Wick, 1995).

1.4.2 Symptoms in Accommodative Dysfunction

There is a wide range of symptoms reported in patients with non-strabismic accommodative and vergence disorders. Accommodative dysfunction can cause significant symptoms, such as blur at near or distance, headaches, asthenopia (eye-strain), difficulty reading and decreased performance after prolonged periods of close work (e.g., reading and computer work), despite having good visual acuity (either corrected or unaided) and lack of identifiable ophthalmic pathology (AOA, 1998; Ciuffreda, 2002). The study of Daum (1983a) is in line with these results, who found that blur (60%), headaches (54%), asthenopia (43%), diplopia (29%), and reading problems (13%) were the most frequently reported symptoms for patients with accommodative dysfunction. Further, Daum (1983a) reported that accommodative problems are most frequently seen in school-aged subjects with the peak being during the early years of college. A study by Chrousos et al. (1988) found the onset of symptoms of asthenopia was between 9 to 18 years of age with a mean of 12.5 years. It has therefore been suggested that measurements of accommodation should be performed more routinely and regularly, especially in children over 8 years old (Sterner et al., 2006). Sterner et al. (2006) further found that below the age of 7.5 years no symptoms were reported during history and symptom taking. This is in line with the results of Scheiman and Rouse (1994) who found that accommodative dysfunction was uncommon in nursery school and first grade children which might be due to a lower accommodative demand due written material often being quite large with good space between lines and around individual words and letters. With progression in school grades, the standard material is made smaller, words and letters are closer and the length of the reading passage increases. At this stage, symptoms of accommodative dysfunction are important to investigate since it is vital that accommodation at near is properly developed when reading is used to learn (AOA, 1998).

	Symptoms
Daum, 1983a	Blur, headaches, asthenopia, diplopia, reading problems
AOA, 1998	Blur, reading problems, asthenopia, poor concentration, headaches

Table 3. The most frequent symptoms of subjects with accommodative dysfunction.

Symptoms in accommodative dysfunction show a strong direct relationship to time spent at a task (Scheiman & Rouse, 1994). One question which is useful to ask is whether reading efficiency declines as a function of time or level of difficulty of the material. If a child reads well the first two or three pages and then the reading abilities collapse, it is strongly suspected to be an accommodative or binocular dysfunction. Around the third or fourth grade, accommodative dysfunction is often detected, however, this can occur both earlier or later (Daum, 1983a; Chrousos et al., 1988; Sterner et al., 2006). The presence of accommodative dysfunction does not necessarily mean that there will be symptoms present. Young children might accept blur and asthenopia as normal or they withdraw from the task at the first sign of difficulty, thus having a negative impact on the overall quality of life – especially in respect to school and work performance (Ciuffreda, 2002). Older children with high motivation are more likely to proceed despite discomfort and often get pain above the eyes which is relieved when resting.

1.4.3 Classification of Accommodative Dysfunction

Accommodative dysfunctions can be classified into five categories: (1) accommodative insufficiency (AI); (2) ill-sustained accommodation (also called fatigue of accommodation); (3) infacility of accommodation (also called inertia or tonic of accommodation); (4) spasm of accommodation (also called excess of accommodation); and (5) paresis of accommodation (also called palsy or paralysis of accommodation). This classification is known as Duke-Elder classification (Ciuffreda, 1998). Among these five, AI is the most prevalent (Daum, 1983a,b; Daum, 1984; Rouse, 1987; Scheiman et al., 1996; AOA, 1998; Rutstein & Daum, 1998; Borsting, 2003). Daum (1983a) has provided a distribution of accommodative dysfunction which can be seen in table 4 (based on 114 persons aged 2 to 37 years). Table 5 provides a summery of the associated clinical findings for the five accommodative dysfunctions.

Dysfunction	Frequency (n)	Percentage
Insufficiency	96	84
Infacility	14	12
Spasm	3	3
Ill-sustained	1	1

Table 4. The distribution of accommodative dysfunction, modified from Daum, K.M. Accommodative dysfunction. *Doc Ophthalmol*. 1983a; 55:177-198.

Summary of Accommodative Dysfunction and Associated Clinical Findings	
Accommodative insufficiency	Lower amplitude of accommodation than expected for the subjects age Low PRA < -1.50D Fails monocular and binocular accommodative facility with minus lenses High lag of accommodation
Ill-sustained accommodation	Initially normal amplitude of accommodation, which decreases with repeated measurements Low PRA Fails monocular and binocular accommodative facility, decreased performance over time High lag of accommodation
Infacility of accommodation	Fails monocular and binocular accommodative facility with plus and minus lenses, with equal difficulty through the lenses Abnormal PRA and/or NRA
Spasm of accommodation	Fails monocular and binocular accommodative facility with plus lenses Low PRA Lead of accommodation Impairment of distance vision

Paresis of accommodation	Reduction of the amplitude of accommodation which does not improve with rest High lag of accommodation Reduced near acuity Dilated pupil

Table 5. A summary of associated clinical findings for the five accommodative dysfunctions. Modified from American Optometric Association (AOA) Optometric Clinical Practice Guidelines. 1998.

1.4.4 Accommodative Insufficiency

Accommodative insufficiency is a condition in which the amplitude of accommodation is constantly below the lower limit of the expected amplitude for the patient's age (Ciuffreda, 1998). AI subjects can also demonstrate a reduced accommodation facility (AOA, 1998) and sometimes an increased lag of accommodation (Rutstein & Daum, 1998). Patients with AI usually suffer from blur, headache and asthenopia associated with near work (Daum, 1983b; Chrousos et al., 1988; Sterner et al., 2006). Patients with AI may attempt to accommodate, and by doing that, stimulate excessive convergence through the AC/A cross-link and could be incorrectly classified as having a convergence excess. In a study of 96 patients who were diagnosed with AI, 59% experienced blur, 56% experienced headaches, and 45% experienced asthenopia. Other symptoms were also present but less frequent (Daum, 1983b). Although these symptoms are bothersome, young adults are able to continue working at near but often with reduced comfort and performance. However, children (age 12 or younger) with AI often avoid near tasks, therefore absence or presence of symptoms is not reliable as a single criterion for diagnosis. On the other hand, if a younger subject reports headaches, asthenopia or discomfort after approximately 15 minutes work, accommodative insufficiency should be suspected. Only refractive error problems have a higher prevalence. As mentioned before, AI is a frequently diagnosed binocular vision anomaly and it has been reported to be the most common cause of asthenopia in schoolchildren between 8 and 15 years of age (Borsting et al., 2003). Clinical signs often described are decreased amplitude of at least 2.00D below the minimum expected age value, lag of accommodation greater than +0.75D with MEM and a failure of mono- or binocular facility (Daum, 1983a,b; Scheiman et al., 1996). Chrousos et al. (1988) concluded that the clinical recognition of accommodation insufficiency is important to prevent unnecessary frustration for these subjects.

The prevalence for AI, which is one of the most common types of accommodative dysfunction, in children of 6 months to 5 years is 0.8% while this number increases to 2.3% for children between 6 to 18 years of age (Scheiman et al., 1996). Scheiman et al. (1996) indicate that accommodative insufficiency was the most common problem in preschool population. Also Borsting et al. (2003) found that AI is a common condition in school-aged children (10.5%) and is associated with increased symptoms. However, several authors who study this dysfunction refer to different diagnostic criteria of AI. Daum (1983a,b) and other authors used the criteria of having 2.00D below Hofstetter's (1944) minimum age amplitude formula to establish low amplitude of accommodation (Dwyer & Wick, 1995; Borsting et al., 2003). Russell and Wick (1993) set the criteria to define AI when the accommodative amplitude was at least 2.50D below the expected age, based on Duane's age norms. Others found that failing monocular accommodative facility with -2.00D lenses seems to be the sign with most association to AI (Cacho et al., 2002). Hokoda (1985), on the other hand, used additional clinical signs to diagnose AI, the monocular accommodative amplitude below 2.00D of Hofstetter's calculation for minimum age and positive relative accommodation (PRA) ≤1.25D. Scheiman et al. (1996) diagnosed AI when the accommodative amplitude was below 2.00D or less than Hofstetter's formula with two of the following four additional signs: low PRA (≤1.25D), failing monocular accommodative facility with minus lenses of ±2.00D flipper lenses, failing binocular accommodative facility with minus lenses of ±2.00D lenses, and a value of MEM dynamic retinoscopy ≥1.00D. A study by Lara et al. (2001) has reported that it is necessary to have four signs present to diagnose AI. Two of the needed signs are reduced amplitude of accommodation, 2.00D below the minimum Hofstetter's (1944) calculation for age, and failing monocular accommodative facility with -2.00D lenses (≤6 cpm). Furthermore, two of three additional signs need to be present: failing binocular accommodative facility with – 2.00D lenses (≤3 cpm), a MEM finding greater than +0.75D, and a PRA ≤1.25D. Borsting et al. (2003) suggest that using Hofstetter's minimum expected age formula my not be the most appropriate for deciding the clinical significance of AI, since their study suggests 2.00D below the minimum expected values is where symptoms are more likely to be associated with AI.

1.5 OPTOMETRIC VISION THERAPY TREATMENT

Vision therapy (also called vision training and orthoptics) has for many years been an important mode of therapy for both children and adults who manifest a range of non-strabismic accommodative and vergence disorders (Rouse, 1987; Abdi et al., 2006). The cure rates for accommodative disorders generally range from 80% to 100% (Daum, 1983b; AOA, 1998). Vision therapy involves purposeful and controlled manipulations of target blur, disparity, and proximity, with the aim of normalizing the accommodative system, the vergence system, and their mutual interactions (AOA, 1998; Rutstein & Daum, 1998; Ciuffreda, 2002). Appropriate manipulation of the blur via lenses and target distance used in vision therapy will maximize the potential improvement in the system and increase sensitivity to blur which will improve the neurosensory sensitivity and increase the amplitude of accommodation in the cases where it had been reduced. There are two main choices of treatment for accommodative dysfunction; refractive correction and vision therapy (exercises). Both types of treatment are used clinically, however, without sufficient scientific data to indicate the underlying mechanism that improves during treatment. With both treatment regimes, the aim is to enhance the ability to alter accommodation quickly and efficiently and to provide visual comfort, especially for near work. The treatment also seeks to increase the ability to maintain accommodation for extended periods and to obtain values expected for the patient's age regarding amplitude, facility and response of accommodation. Several factors should be considered when determining whether to recommend refractive correction or vision therapy. From the literature, it is not clear which treatment method will give the most effective result or which strength the refractive correction should have.

In a study by Liu et al. (1979) where the subjects were treated with step dioptric blur stimuli, i.e., jump focus and lens flippers, and ramp dioptric blur stimuli, i.e., pencil push-up, showed an objective change in velocity of the accommodative response and

simultaneous decrease in recorded time constants. They suggested that the reduction in latency may indicate a more efficient signal processing at the cortical level, whereas the increased rate of accommodative change represents a greater rate of force output by the neuromuscular system. Similar results of the speed of accommodation were found by Bobier and Sivak (1983) who also found that the treatment effects persisted after a 4.5 month follow-up. Another study showed that the positive effects after training was still maintained after 6 to 9 months, the near work related symptoms were markedly reduced, and the accommodative facility was improved (Hung et al., 1986). In 1987 Cooper et al. conducted a double blind study on subjects with accommodative dysfunction with the prime purpose of determining if accommodative therapy reduces asthenopia. They concluded that their results are not due to experimental bias or placebo; rather it appears to be a direct function of the improvement in the amplitude of accommodation, speed and sustained time of accommodation. A study by Sterner et al. (1999) on school-age children who manifest accommodative dysfunction showed that accommodative facility therapy, i.e., lens flippers, relieved symptoms such as asthenopia, headache, blur and avoidance of near work. Further, the majority of subjects (20 of 38 children) still remained asymptomatic after a two-year follow-up. Orthoptic treatment of convergence insufficiency has shown that is possible to change both the fast and slow vergence components of the accommodative and vergence system (Brautaset & Jennings, 2006). These studies demonstrate that accommodative vision therapy can change the amplitude and facility of accommodation and decrease symptoms. Therapy can also improve the time characteristic, both the latency and velocity, and magnitude of the accommodative response, and can produce true physiological alterations in the accommodative system with a persistent result.
Early detection and treatment of children is ideal especially if the AC/A ratio is high and accommodation could result in an esotropia at near. Thus, examination of children is important at a young age (AOA, 1998).

The two most important vision therapy regimes for AI are plus lens reading additions (PLRA) and orthoptic exercises such as spherical flippers (Daum, 1983b; Mazow et al., 1989; Rutstein & Daum, 1998), however, the two regimes of therapy are fundamentally different. PLRA is a relatively passive mode of therapy in which the accommodative system is given a “helping hand” in getting a clear retinal image. The amount of blur on the retina when wearing the PLRA is less than while not wearing the plus addition. The role of the PLRA is therefore to reduce blur to such an extent that the remaining blur is recognized and within the subject’s accommodative capacity. The subject’s task is to recognize the remaining image blur and to clear the image. By being able to clear the image, the blur driven sensors (fast component) and the adaptive mechanism within the accommodative system will start to regain normal capacity (Ciuffreda, 2002).
With spherical flippers the initial amount of blur is not reduced. However, a controlled amount of additional blur (with the negative side of the flipper) and a controlled amount of reduction in blur (with the positive side of the flipper) is induced each time the flipper is alternated between the negative and the positive lens sides. The subject’s task is to recognize the change in defocus of the image and try to respond by obtaining a clear image. By being able to recognize and respond to the blurred image, the blur driven sensors (fast component) and the adaptive mechanism within the accommodative system will start to regain normal capacity (Ciuffreda, 2002). Chrousos et al. (1988) concluded that appropriate spectacle correction, such as reading glasses or

bifocals, with the weakest plus lens that allows comfortable vision at near should be prescribed so that the accommodation may be exercised and stimulated rather than completely relieved.

1.6 OCULAR ABERRATIONS

In order to have good visual quality, the optical system should create a clear image on the retina. However, the optics in the refractive system is not perfect, and even small imperfections in this process will lower the quality of vision. There are different factors affecting image quality; one of them is aberrations. Aberrations can be divided into chromatic aberration (CA) and monochromatic aberration. Chromatic aberration will arise in the eye when white light (polychromatic light) is refracted; long wavelength (red light) is less refracted than the short wavelengths (blue light). Theoretically, the total longitudinal CA for all visible wavelengths will be more than 2.00D (Helmholtz, 1962), however, for wavelengths between 486-656 nm it will be about 1.00D, and even less at low luminance levels (Bradley, 1992). In polychromatic light and under photoptic conditions, the eye is most sensitive to light of 555 nm (Ciuffreda, 1998). By using monochromatic light it is possible to eliminate CA, and then only monochromatic aberration will be present.

As mentioned in section 1.2.1, the accommodative system has different components which contribute to the final accommodative response, the reflex accommodation response to blur being the most important. Blur is an even-error signal, i.e., it gives the magnitude of the accommodation, but lacks the directional information. Therefore, it is dependent on other cues to know whether accommodation needs to be increased or reduced. The main directional cues for the accommodative system are thought to be CA and spherical aberration (SA) (Fincham, 1953; He et al., 2000; Appelgate, 2004; Cheng et al., 2004; Chin et al., 2009), but even proximity has been suggested, and under binocular conditions directional information is obtained through the convergence accommodative cross-link (Fincham, 1951; Cuiffreda, 1991). It has been suggested that the brain might learn the nature of the necessary adjustment of accommodation, and this learning effect could be based on chromatic aberration of the eye (Fincham, 1951).

1.6.1 Monochromatic aberrations

Aberrations in an optical system mean that not all light is focused to a limited spot on the retina; it is deviated and blurs the image. Monochromatic aberration is divided into Lower Order Aberration (LOA) and Higher Order Aberration (HOA), see figure 6. The LOA includes defocus, i.e., refractive errors of myopia and hyperopia, and astigmatism which can be corrected by spectacles, contact lenses or refractive surgery. The HOA includes, e.g., coma, trefoil and SA. Both LOA and HOA will affect the quality of the image (Appelgate, 2004). The HOA are more difficult to correct than the LOA. However, the HOA do not deteriorate the retinal image as much as refractive error does. The amount and kinds of HOA varies between individuals, but comparison between the left and right eye usually shows mirror symmetry (Porter et al., 2001). The influence of HOA increases with pupil size and the reason is that the rays coming in the eye peripherally are refracted at a larger angle. During daylight, the aberrations will have a small effect on foveal image quality since the pupil diameter is often small, meanwhile during the night the aberrations will affect the image quality more, which becomes evident to many people during night driving.

One way to explain the image quality is to use the point-spread function (PSFs), i.e., the image of a point object, which gives a visualization of the aberrations. To quantify the amount of HOA, the RMS-value (root-mean-square) is used, i.e., the RMS of the wavefront aberration without the refractive errors. The RMS-value gives a rough estimation of whether the eye has large aberrations or not. The higher the RMS wave-front error, the worse the image quality. Studies have shown that the RMS does not change for accommodation up to 3.00D, however, large amounts of accommodation have been shown to cause a significant difference in aberrations as compared with the relaxed state (He et al., 2000; Cheng et al., 2004). Aberrations are often measured on the wavefront that propagates out of the eye from a point on the retina. If the eye is emmetropic and without aberrations, the wavefront would be plane. The wavefront measured is often reconstructed with polynomials and the standard today is to use Zernike polynomials (see figure 6).

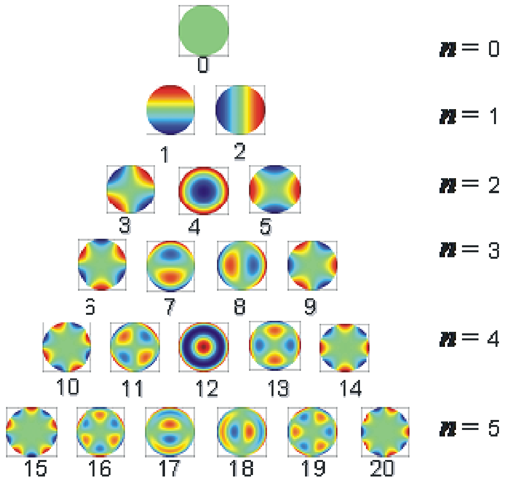

Figure 6. The Zernike polynomials. Order (n) 0 to 2 are the LOA and order 3 to 5 is the HOA. The picture is published with consents from the painter (Unsbo & Lundström).

The zero and first order (n=0 and n=1) have no relevance for the aberration of the eye. The second order (n=2) term correspond to the refractive errors. The third and fourth (HOA) order terms includes, e.g., coma, trefoil and spherical aberration where the last mentioned is one of those thought to give directional cues for the accommodative system (Fincham, 1951). Together, the Zernike polynomials and the Zernike coefficient can describe any wavefront over a circular pupil.

1.6.2 Spherical aberration and accommodation

Spherical aberration occurs when there is a lack of coincidence of focus between the off-axis (peripheral marginal) rays and the on-axis (central) rays. When the peripheral rays come to a focus in front of the central rays it is referred as positive SA, which is the most common SA in the unaccommodated eye. However, negative or overcorrected SA can be found and occurs when the central rays comes to a focus in front of the peripheral rays. The SA will change almost linearly with the level of accommodation, changing from a positive value in the unaccommodated eye to becoming negative in the accommodated eye (He et al., 2000; Cheng et al., 2004; Plainis et al., 2005). The change in aberrations is due to the crystalline lens changes in shape, position and refractive index (He et al., 2000; Cheng et al., 2004). There are several directional cues to the accommodative system which are subdivided into optical and non-optical cues, e.g., CA, SA, astigmatism, microfluctuations, proximity and disparate retinal images. Depending on these cues, the accommodative system will know which direction accommodation needs to be changed (Ciuffreda, 1998). It is commonly stated that SA and CA are the strongest inherent stimuli for directional control within the accommodative system. Of the LOA, it is defocus that changes the most but astigmatism also varies. Regarding the HOA, it will be SA and coma which change the most during accommodation (He et al., 2000; Cheng et al., 2004; Plainis et al., 2005). It has been indicated that spherical aberration is not a strong directional cue to accommodation, at least not when accommodation is changed in large steps (Atchison et al., 1995b). However, this is not in line with the recent results of Theagarayan et al. (2009), who found that the accommodative lag was affected when altering SA. On the other hand, the negative changes in SA induced by Theagarayan et al. (2009) were much larger in amount than what normally occurs in the human eye. Also Chin et al. (2009) indicate that SA might play a significant role in controlling accommodation. However, a study of Cheng et al. (2004) concluded that at moderate accommodative levels of 1-3D, showed no difference in accommodative response when correcting SA or not.

1.6.3 Correcting aberrations with contact lenses

There has been great interest recently in the use of contact lenses to correct aberrations in order to create improved image quality. To best achieve that, it would be ideal to customize contact lenses; however, that is currently too costly. Spherical aberration is the only one of the HOA that is possible to correct with standardized contact lenses, which are based on an average value of the normal population (Porter et al., 2001; Thibos et al., 2002). The average amount for a 6 mm pupil is approximately 0.1±0.1 µm (Thibos et al., 2002; Wang et al., 2003). Aberration controlled contact lenses have the intention of either reducing SA in order to improve image quality (i.e., these lenses are in nature multifocal but are called “single vision aspheric lenses”), or increasing SA to create a reading addition, i.e., these lenses are also multifocal and are called “multifocal contact lenses” since they intend to offer a reading addition. Since a spherical surface induces SA, the SA can be reduced by altering the lens form. For a single vision lens, SA can be minimized by changing the curvature of the surface by using aspherical curves which compensate for the refractive effects in the periphery and vice versa for a multifocal contact lens where aspherical curves will create an addition. Since SA is a rotationally symmetric aberration, an aspheric front curve can be chosen to create negative spherical aberration to neutralise the typical unaccommodated eye’s positive spherical aberration.

Theoretically, aberration controlled contact lenses offer a possibility to increase visual quality through correction the SA and thereby improve the image quality (Plainis et al., 2005). The SA controlled contact lens is commonly fitted but has not been found to have any clinical effect on image quality (Efron et al., 2008; Lindskoog Pettersson et al., 2011). Previous studies have shown that these lenses do reduce the amount of spherical aberration in the unaccommodated eye (Efron et al., 2008, Lindskoog Pettersson et al., 2008). One study found that their was no significant difference between an spherical and aspheric contact lenses in high- or low-contrast visual acuity, but the subjects preferred the aspheric design (Vaz & Gundel, 2003). However, in recent studies, distance visual acuity and contrast sensitivity was found to be unaffected by these lenses as compared with spherical lenses even though spherical aberration was reduced (Efron et al., 2008; Lindskoog Petterson et al., 2011). There are not many studies on multifocal contact lenses' effects on accommodation, however, Tarrant et al. (2008) evaluated the effect of bifocal contact lenses on accommodative lag in young adults (mean age 22.8 ± 2.5 SD). Further, they found that the lens induced a lead of accommodation (Tarrant et al., 2008). The result that one would expect is that the accommodation would have been relaxed when looking through a bifocal contact lens. However, further studies are needed to evaluate what effect multifocal contact lenses might have on the accommodative response of younger subjects.

2 AIMS OF THE PROJECT

The aim of this thesis was to evaluate the efficiency of different regimes of treatment for AI. A further, more theoretical aim was to evaluate the effect on accommodation when reducing and removing the directional cues of SA and CA and when correcting young subjects with multifocal contact lenses.

Paper I
To evaluate the outcome of accommodative insufficiency treatment with plus lens reading addition and accommodative flexibility exercises.

Paper II
To evaluate the outcome of accommodative insufficiency treatment with +1.00D lenses and +2.00D lenses.

Paper III
To investigate the effect on accommodation when manipulating the directional cues to accommodative response, i.e., spherical aberration and chromatic aberration.

Paper IV
To study the effect on accommodation when using a multifocal contact lens, i.e., spherical aberration modified lens, with addition +1.00D for near in normal subjects and subjects with accommodative insufficiency.

2.1 MATERIAL AND METHODS

2.1.1 Material/Data Collection

The subjects in Papers I and II were recruited when seeking help of an orthoptist due to asthenopic symptoms. At their visit to the orthoptist (Examiner 1), they were consecutively asked to participate in the study if they met the inclusion criteria. In order to be included as an AI subject, the following criteria had to be met, see table 6 (measurements were performed by Examiner 1 as part of the inclusion examination).

Paper I and II
▪ Symptoms according to history revealing uncomfortable vision, blur and/or headache. ▪ Normal ocular motility and all three figures on the Lang II stereo vision test needed to be visible. ▪ Cycloplegic (cyclopentolate 0.75% and phenylephrine 2.5%) refractive error less than 1.00D of hypermetropia and less than 0.50D of myopia, and/or astigmatism less than 0.50D. ▪ Distance heterophoria between 2Δ of exophoria and 2Δ of esophoria and near (40 cm) heterophoria between 6Δ of exophoria and 4Δ of esophoria.

▪ Near point of convergence of 10 cm or better on the RAF (Royal Air Force) rule. ▪ Near point of accommodation worse than (100/(15D-(0.4 age)))[1] on the RAF-rule. ▪ Opposing fusional reserves of at least twice the near phoria (fulfilling Sheard´s criterion). ▪ Distance Snellen visual acuity of 20/25 (0.8) or better both monocularly and binocularly. ▪ No ocular pathology (examination of media and fundus) and no history of ophthalmologic treatment. ▪ Not taking any medication with a known effect on visual acuity and/or binocular function and accommodation.

Table 6. The inclusion criteria for paper I and II. The following criteria had to be met to be included as an AI subject.

In paper I and II there were 24 (10.3 years, ±2.5 SD) and 22 (11.8 years, ±3.54 SD) AI subjects included, respectively.
All the subjects in Papers III and IV were recruited among students at the School of Optometry, Karolinska Institute, Stockholm, Sweden, additionally AI subjects in Paper IV were recruited from the Open Optometric Clinic at the School of Optometry. The following inclusion criteria had to be met for Paper III and IV, see table 7.

Paper III	Paper IV
▪ Refractive error between -10D to +6D (in order to be in range of the power of the contact lenses) and astigmatism less than 0.75D (in order to achieve a high level of visual acuity when corrected with non-toric contact lenses). ▪ No ocular pathology or systemic disorder and not taking any medication with a known effect on accommodation or any other aspects of vision.	▪ Habitual spectacle correction within ±0,25D of the refractive error determined as a part of the study (in order to ensure that the habitual correction could be used when measuring the study variables). ▪ No ocular pathology or systemic disorder and not taking any medication with a known effect on accommodation or any other aspects of vision.

[1] This calculation of the minimum accommodative amplitude is based on Hofstetter's (1944) comparison of Duane's and Donders table of the amplitude of accommodation. Hofstetter calculated that the minimum normal accommodative amplitude should be regarded as (100/(15D – (0.25age))); this formula yields an accommodative amplitude in cm. In this study, we used the formula (100/(15 – (0.4age))) in order not to include subjects with normal but low accommodative amplitude.

▪ Distance visual acuity with ETDRS (Early Treatment Diabetic Retinopathy Study) of 20/20 (1.0) or better monocularly. ▪ Younger than 35 years of age (in order to ensure a reasonable amplitude of accommodation). ▪ No corneal abnormalities based on keratometry readings and slit lamp inspection.	▪ Distance visual acuity with ETDRS (Early Treatment Diabetic Retinopathy Study) of 20/20 (1.0) or better monocularly. ▪ Stereo acuity with the TNO (random dot) stereo test of 60 sec or better. ▪ No corneal abnormalities based on keratometry readings and slit lamp inspection.

Table 7. The inclusion criteria for the normal group in paper III and IV.

Twenty subjects were included in both Papers III and IV, with a mean age of 25.0 (±2.37 SD) and 25.9 (±4.3 SD), respectively. The AI subjects in Paper IV were included based on the same criteria as mentioned for AI subjects in Paper I and II. The AI subjects were aged between 10 and 18 years with a mean age 12.4 years (±3.2 SD).

2.1.2 Methods

In study I and II the study variables measured were: (1) near point of accommodation on the RAF-rule (three repeated measurements both monocularly and binocularly, the average value was calculated for the analysis); (2) lead/lag of accommodation as measured with Nott dynamic retinoscopy (for Paper I) or with MEM technique (Paper II), while fixating a vertical row of letters equivalent to 20/30 (~0.6) visual acuity at 40 cm; and (3) subjective grading of the degree of asthenopia on a Visual Analogue Scale (VAS). The question asked with the VAS was “If 0 equals no problem when doing near work and 10 equals the worst degree of problems, what number would you grade your problems at near work to be now?” Paper I also included variable (4); accommodative facility at 40 cm with a ±2.00D flipper while fixating a vertical row of letters equivalent to 20/30 visual acuity (measured binocularly and in the dominant eye, dominance was tested with the Miles test (Michaels, 1975)). These measurements were done without any reading addition, and the near point of accommodation was recorded as a mean of the measurements. The variables were measured both pre- and post the treatment period of eight weeks. The treatment given in study I (Paper I) was either spherical flipper treatment with a ±1.50D flipper or +1.00D PLRA, according to randomized list. In study II (Paper II) the treatment given was PLRA of either +1.00D or +2.00D, the power of the reading addition was unknown for the subjects.
The subjects in study I were instructed to use the spherical flipper treatment two sessions of nine minutes each day. The sessions were to be done at times when the subjects were not feeling tired or experienced asthenopia. The flipper was to be done at 40 cm. The subjects did as many “flips” as possible for one minute. This was followed by another one-minute trial of flipping and a one-minute break. This sequence was repeated until the subject had done a total of five minutes of flipping. Each subject was also given a fixation target (vertical row of letters equivalent to 20/30 visual acuity at 40 cm). For the PLRA treatment, in both Papers I and II, the subjects were encouraged

to use the PLRA as much as possible for all types of near visual work and to try making the image as clear as possible. The subjects in Papers I and II were initially seen by Examiner 1 to determine if they met the inclusion criteria. If they were included, Examiner 2 (a second person) then determined the study variables Without knowing the results from Examiner 1. Then the subjects received their treatment from either Examiner 3, a third person (in study I), or by Examiner 2 (in study II). After eight weeks of treatment, all subjects were re-examined by Examiner 2.

In Paper III, the aberrations of the dominant eye of the subjects were measured with a Zywave™ aberrometer (Bausch & Lomb, Surgical, Salt Lake City, Utah, US). The wavefront aberrations were measured in the uncorrected eye (UC), with trial frame correction (TFC), and with spherical aberration controlled contact lens (SACL) correction. The PowerRefractor (MultiChannel Systems, Reutlingen, Germany – now manufactured by PlusOptix, Nürnberg, Germany) was used to measure ocular accommodation with the TFC and SACL, with a -2.00D lens used as accommodative stimulus. The subjects were fitted with a spherical aberration controlled contact lens (SACL), PureVison™. The accommodation measurement was done under both polychromatic and monochromatic light conditions.

In Paper IV, the aberrations of both eyes of the subjects were measured with a Zywave™ aberrometer (Bausch & Lomb, Surgical, Salt Lake City, Utah, US). Wavefront aberrations were measured in the uncorrected eye and with a multifocal contact lens, Proclear™ Multifocal. A Shin-Nippon N Vision-K 5001 (Shin-Nippon, RyoSyo Industrial Co.Ltd, Japan) was used to obtain a baseline over-refraction with distance fixation and for measurements of accommodative response at near (40 cm). The near target was placed directly in front of the right eye and a physical septum was used to prevent the left eye from seeing the target. Distance over-refraction and accommodation were measured with two different refractive corrections: (1) habitual spectacle correction only, and (2) habitual correction and a plano multifocal contact lens.

2.1.3 Additional Information on the Equipment Used in the Studies

2.1.3.1 PowerRefractor

The PowerRefractor (MultiChannel Systems, Reutlingen, Germany – now manufactured by PlusOptix, Nürnberg, Germany) is a videorefractometer that measures refractive errors in both eyes simultaneously and is based on the principle of eccentric photorefraction, i.e., the infrared light is eccentric to the optical axis of the camera. All photorefractors works on the principle of analyzing the vergence of reflected light rays returning to a camera after illuminating a point on the retina. The PowerRefractor has a camera which is surrounded with six infrared light diodes (working as a retinoscope). The infrared lights illuminate in succession and the light reflected from the retina is analyzed by the software. The PowerRefractor is an ideal apparatus for the screening of refractive errors (Abrahamsson et al., 2003) and it also allows continuous measurement at a frequency of 25 Hz. The data is presented as sphere, cylinder (in 0.25D steps) and axis for each eye (1° increments). In addition to refractive measurements, the PowerRefractor can also determine the interpupillary distance, eye position, pupil size, and the dynamics of accommodation. Several studies have shown that the

PowerRefractor is a reliable tool to measure refractive errors in young children (Choi *et al*., 2000; Abrahamsson et al., 2003; Hunt et al., 2003).

2.1.3.2 Zywave

The Zywave™ aberrometer (Bausch & Lomb, Surgical, Salt Lake City, Utah, US), is based on the Hartman-Shack wavefront technique (Liang & Williams, 1997). During a Zywave measurement, five consecutive wavefront measurements are made and the software then discards two outliers and then calculates the mean aberrations (Mirshahi, et al., 2003; Efron, et al., 2008). The wavefront measurement should be performed three times and then average wavefront aberrations are calculated. The aberration measurement was performed in a dark room and the subjects are covered with a dark cloth to get maximum pupil size without the use of dilation. All aberrations are measured in the relaxed eye, i.e., target set at infinity, but 0.30D of instrument myopia is expected with the auto-aberrometer.
Based on the wavefront data for the maximum pupil size obtained with the Zywave™, analytical scaling of the data can be done with the method described by Lundström and Unsbo (2007) to calculate the aberrations for pupil sizes 4.0, 5.0 and 6.0 mm.

2.1.3.3 Shin-Nippon

The Shin-Nippon N Vision-K 5001 Autoref-keratometer (Shin-Nippon, RyoSyo Industrial Co.Ltd, Japan) can measure refraction at distance and at near. The instrument also displays keratometry values. The NVision-K is an open view autoref-keratometer and allows binocular fixation through the instrument. The NVision-K has three measurement modes: both autorefraction and keratometry simultaneously, keratometry alone, and refraction alone. The NVision-K is equipped with a high-speed function to allow for continuous measurements, and the settings can be changed for measurements at near. The data is presented as sphere, cylinder and axis for each eye in 0.25/0.12D steps. The instrument can take up to 106 static prescription readings in 1 min in the ranges of ±22.00D sphere and ±10.00D cylinder in steps of 0.12D for power and 1° increments for the cylindrical axis (Davies *et al*., 2003). Keratometric parameters are presented as a radius of curvature or corresponding refractive power. For a more detailed description of the Shin-Nippon N Vision-K 5001 Autoref-keratometer see Davies et al. (2003).

2.1.3.4 Contact lenses

The contact lens used in Paper III was a PureVison™ contact lens, which is a single vision monthly disposable silicone hydrogel contact lens, intended to correct spherical aberration by –0.15 µm in all powers over a 6.0 mm pupil (Bausch & Lomb Incorporated Rochester, NY, US). The value of -0.15 µm is based on an average value in the population. The lens is based on aspheric design.

The multifocal contact lens used in Paper IV was a Proclear™ Multifocal contact lens (CooperVision Ltd, Hamble, UK) which is based on aspheric design in which a more hyperopic refractive power is achieved in the peripheral parts of the lens, see figure 7. The aspherical zone of 5 mm will have full addition of +1.00D when entering the second spherical zone.

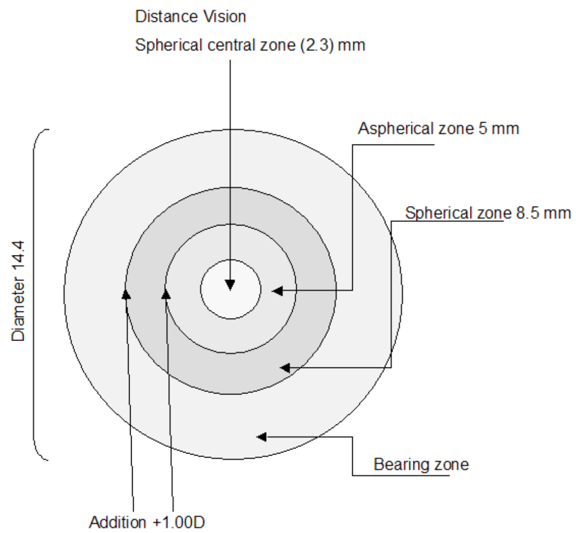

Figure 7. Shows the Proclear™ Multifocal lens design.

2.1.3.5 Visual Analogue Scale – VAS

The VAS scale used in study I and II is a common method for evaluating the subjective severity (and relief) of pain or discomfort (Kelly, 2001). The scale is presented as a 10 cm long line. It is the subject's task to grade his or her pain using this scale, from none to an extreme amount of asthenopia, where "none" and "extreme" anchor the VAS at each end. Previous study of asthenopia (ocular pain or discomfort) using the VAS scale has shown to be a useful method to indicate when symptoms have been relieved (Abdi et al., 2006).

2.1.4 Ethics

Ethical approval was given by the local ethical committee and the studies adhered to the declaration of Helsinki. The subjects received written information and informed consent was obtained from all the participants before the study.

2.2 RESULTS

2.2.1 Paper I

In this study the analysis of accommodative function showed a significant interaction between the study variables (near point of accommodation, accommodative facility, accommodative response and subjective grading) and the treatment. The analysis of the accommodative amplitude showed a significant change, the improvement was 1.60D in

the PLRA group and 3.60D in the flipper group. Accommodative facility increased with 1.25 cpm, on average, for the PLRA group and with 1.51 cpm in the flipper group, which was close to significant (p=0.06). The accommodative response did not change. For details see table 8.
The analysis did not reveal any statistically significant difference between the two therapy regimes (p=0.58). With the accommodative response excluded, the difference was still not significant.
Regarding the subjective feeling, both the flipper and PLRA group experienced reduced level of asthenopic symptoms after treatment as indicated by the reduced VAS score. The average VAS score for the PLRA group was 4.7 units lower after treatment and the flipper group was 6.3 units lower after treatment.

	PLRA (n=10)			**Flipper (n=9)**		
Variables	**Before**	**After**	**Diff**	**Before**	**After**	**Diff**
Acc amp (DS)	3.58 ± 0.81	5.16 ± 2.15	1.58**	4.25 ± 1.83	7.82 ± 4.51	3.57*
Acc fac (cpm)	5.55 ± 3.22	6.80 ± 2.42	1.25	4.66 ± 2.42	6.17 ± 3.54	1.51
Lag (D)	0.34 ± 0.33	0.30 ± 0.41	-0.04	0.32 ± 0.44	0.34 ± 0.51	0.02
VAS	7.3 ± 0.95	2.6 ± 0.52	-4.7**	8.11 ± 0.78	1.77 ± 1.30	-6.34**

*=Wilcoxon matched pair test *=p≤0.05; **=p≤0.01

Table 8. Average values (± SD) of the study variables before and after treatment [Acc amp, accommodative amplitude with the RAF-rule; Acc fac, accommodative facility with a ±2.00D flipper; Lag, lag of accommodation; VAS, Visual Analogue Scale results].

2.2.2 Paper II

Accommodation treatment was compared between +1.00D and +2.00D reading addition in two groups of AI subjects. To ensure that the groups did not differ from each other before treatment they were compared and the analysis showed no statistical significant difference regarding to the accommodative amplitude and response, or in VAS score when comparing the groups. After treatment, there was a statistically significant increase in accommodative amplitude in the +1.00D group, whereas no difference could be found in accommodative response and VAS score when comparing the two groups.
The analysis showed a significant change in the binocular accommodative amplitude, which improved on average by 3.28D for the +1.00D reading addition group (p <0.05). In the +2.00D reading group the improvement was on average 1.36D, which was not significant. The accommodative response did not change for either of the treatment groups. Regarding the subjective impression, both the +1.00D reading addition group and +2.00D reading addition group experienced a reduced level of asthenopic symptoms after treatment as indicated by the reduced VAS score. The average VAS score for the +1.00D reading addition group was 3.21 units lower after treatment and for the +2.00D reading addition group it was 5.57 units lower after treatment. The reduction in VAS score was significant in both groups. For details of the results, see table 9.

	Plus 1.00D reading addition (n=10)			Plus 2.00D reading addition (n=10)		
Variables	**Before**	**After**	**Diff**	**Before**	**After**	**Diff**
Acc amp (D) Binocularly*[a]	6.12± 2.03	9.41 ± 5.69	3.28*[d]	5.06 ± 2.34	6.42 ± 3.62	1.36
Lag (D)	0.50 ± 0.24	0.43 ± 0.26	-0.07	0.37 ± 0.13	0.37 ± 0.18	0.00
VAS	5.44 ± 2.39	2.24 ± 2.50	-3.21*[b]	7.36 ± 1.56	1.80 ± 1.52	-5.57*[c]

*[a] =Mean values of the three measurements. *[b]=Wilcoxon match pair test, p <0.05, *[c]= Wilcoxon match pair test, p <0.001. *[d]=Bonferroni multiple comparison test, p <0.05.

Table 9. Average values (± SD) of the study variables before and after treatment [Acc amp, accommodative amplitude with the RAF-rule; Lag, lag of accommodation; VAS, Visual Analogue Scale results].

2.2.3 Paper III

In this study, the statistical analysis of twenty subjects showed no difference in the amount of SA comparing UC and TFC corrections (p>0.05) for all three pupil sizes. However, SA with SACL correction was found to have a statistically significant negative shift (p <0.001) as compared with both UC and TFC correction over all three pupil sizes. Further, the study showed no difference in the amount of RMS when comparing UC, TFC or SACL corrections (p>0.05) for all three pupil sizes.
The measurements of accommodation showed that the time for the subjects to accommodate from 2% to 98%, i.e., accommodation response time, showed no significant difference (p >0.05) between TFC and SACL corrections in chromatic or monochromatic light. Furthermore, no statistically significant difference could be found for the peak velocity and the size of the accommodative lag between TFC and SACL corrections under the two light conditions. A regression analysis of SA/velocity and RMS/velocity was done, the R^2 –values were 0.02 and 0.06, respectively, which means that no correlation between SA and velocity or RMS and velocity could be found.

2.2.4 Paper IV

In the group of normal subjects, the mean accommodative lag was 0.85D (±0.57 SD) and 0.75D (±0.52 SD) without and with the multifocal lens, respectively. Statistical analyses showed no difference in lag (t = 0.8479, p = 0.407). The lag with and without the multifocal lens was not correlated with pupil size nor with the amount of spherical aberration. A correlation plot was done between the pupil size and lag of accommodation (R^2=0.0016) and spherical aberration and lag of accommodation (R^2=0.0011) while wearing the multifocal lens, but no correlation could be found.
In the AI subjects, the lag was 0.57D (±0.91 SD) and 0.70D (±0.67 SD) without and with the multifocal lens, respectively. The number of subjects was too low to make any statistical comparison.

2.3 DISCUSSION

The treatment of functional accommodative dysfunction has included plus lens addition for near work or therapy aimed to strengthen the accommodative mechanisms. In the first study the purpose was to evaluate which mode of therapy, PLRA or spherical flipper, was more effective in the treatment of AI. The result showed no statistical significant difference between these two regimes, which indicate that both are efficient to improve the response of the blur driven sensors and the adaptive mechanisms. These results are in line with other studies (Liu et al., 1979; Daum, 1983a,b; Rouse, 1987). Schors' (1979a, 1986) model describes the relationship between the fast and slow component and the mutual interactions between the accommodative and vergence system. In study I the fast component of the accommodative system was measured with the flip lens technique. The result showed that the subjects had a lower value than expected for their age. These results are in line with Garcia (2000) who found that there is a relationship between reduced accommodative facility and binocular and accommodative dysfunctions. Another study of accommodative facility showed that symptoms such as asthenopia would be likely to be present when subjects complete between 3 and 8 cpm binocularly, which is true for the subjects in study I. These results indicates that the fast component is not working as fast and accurate as expected, which results in low flexibility for subjects with AI. A possible reason for the decreased flexibility could be due to decreased adaptation of the slow component, which will result in fatigue in the fast system (Schor, 1980). On the other hand, the neural coding of the fast component could be decreased or poor and the input to the slow component might be to insufficient for it to take over. Previously studies found an inverse relationship between slow adaptable component of accommodation and the AC/A ratio which means that a weak adaptation of accommodation will create a high AC/A ratio (Schor & Tsuetaki, 1987; Schor, 1988; Schor & Horner, 1989). Subjects with high AC/A ratio have showed to have a low CA/C ratio, which confirm that there is inverse relation between the two directions of cross link (Schor & Horner, 1989). If the AC/A and CA/C ratio have normal values, the interactions reach a state of balance where each controller achieves a realistic output (Schor, 1983b). These findings indicate that subjects with AI would have a high AC/A ratio due to weak adaptation consequently followed by a low CA/C ratio, which could contribute to a robust adaptation of the vergence system. That means an imbalance between the systems. This will then affect the output to the muscles of each system, see figure 8 for an illustrative model of possible reasons to AI. However, have orthoptic exercises showed to a have a positive effect on treatment of subjects with accommodative and binocular dysfunctions (Daum, 1983b; Schor, 1988; Mazow et al., 1989; Rutstein & Daum, 1998; Braustaset & Jennings, 2006), where both the fast and slow component is improved.

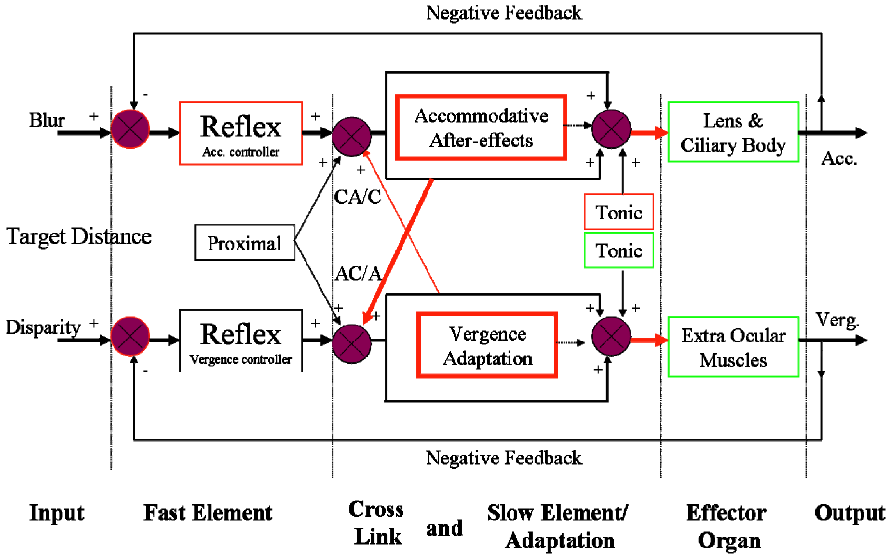

Figure 8. Illustrates possible components which might sustain an error for AI subjects. The red lines marks the possible components of error.

Plus lens addition has been shown to alleviate the symptoms of AI subjects (Abdi et al., 2006; Brautaset et al., 2008; Wahlberg et al., 2010) to the same extent as orthoptic treatment (Daum, 1983b). Additionally, it has been suggested that patients with AI not seen frequently by the examiner might benefit from PLRA rather than vision therapy (Russell & Wick, 1993). This is in agreement with study I in where the compliance was better with PLRA than with flipper treatment (five drop-outs from the flipper treatment group and non from the PLRA). For the subjects with AI it is reasonable to assume that a reading addition of more than +1.00D will alleviate symptoms. However, it was not known at the time of the study whether the blur would be reduced to such an extent that the blur driven sensors and adaptive mechanism would be completely relieved and no longer exercised. Therefore, in study II the purpose was to evaluate if +2.00D lens reading addition has the same effectiveness as +1.00D reading addition in the treatment of AI. The results of +2.00D reading addition treatment showed a small improvement of the amplitude after treatment which was not significant while the increase of the amplitude was significant with +1.00D. This indicates that the blur is reduced to such an extent that the remaining blur is too small in order to exercise the accommodative system. These results are in line with Chrousos et al. (1988) who concluded that only the weakest plus lens addition which allows comfortable vision at near should be prescribed so that the accommodative system can be exercised and stimulated rather than completely relieved. Studies on subjects with normal binocular vision have shown that when fixating through +2.00D lenses an initial increase in exophoria and CA/C occur. Prolonged fixation initiated vergence adaptation (Sreenivasan et al., 2008; Sreenivasan et al., 2009).

Further, in study II, the subject subjectively graded the degree of asthenopia on a VAS scale where a previous study of asthenopia using the VAS scale have shown that a grading of 2 or less can be regarded as normal for children with asthenopia without any ocular pathology (Abdi et al., 2006). It has been found that subjects with AI tend to grade a higher score than subjects with normal binocular vision (Bortsing et al., 2003), however, they did not use the same subjective score record as used in the present studies. The reduction in VAS score after treatment was significant for all treatment groups in both studies, but only in the flipper and +2.00D reading addition group was the average VAS score below 2 achieved. The reason for that could be due to that spherical flipper might exercise the system more than reading addition. It could at first be thought of as conflicting that the +2.00D reading addition group achieved a Vas score below 2, while their was no significant improvement in their accommodative capability. The explanation for this finding is most likely that the VAS score reflects the amount of effort that has to be exerted while reading. With +1.00D reading addition the subjects have to exert and exercise their accommodation, and asthenopia will only be graded at a level below 2 when accommodation has reached normal levels. In the +2.00D reading addition group accommodation does not need to be exerted since the reading addition eliminates more or less all blur present. The subjects are therefore likely to report their asthenopia as being alleviated. The above argument is based on the belief that improvement is only achieved if the accommodative mechanism is improved; however, success could also be defined by a reduction in symptoms alone. In that case, the +2.00D treatment regime is the most successful method. However, I believe that success should be based on actual improvements in accommodative function and not only relief of symptoms, since the intention is to treat the patients.

To achieve success in treating subjects with AI, I think it is of importance to follow the patient regularly at the clinic (once a week in the beginning, and to combine the therapy exercises with PLRA). I would recommend PLRA of +1.00D for all near related work (including computer, reading, and writing), to relieve and improve the accommodation, and also twice daily sessions of spherical flipper training of 10 minutes each. By decreasing the demands of the accommodation with +1.00D reading addition, which still demand a bit of work of the patient, the symptoms will decrease and the patient will also have strength to perform flipper exercises.

As previous studies have indicated, both CA and SA may to some extent serve as directional cues for accommodation (Fincham, 1951; He et al., 2000; Appelgate, 2004; Cheng et al., 2004; Chin et al., 2009; Theagarayan et al., 2009). Therefore, the aim of study III was to evaluate different aspects of the accommodative response under both mono- and polychromatic light while varying the amount of spherical aberration. The results of SA with the SACL on the eye are in line with (Lindskoog et al., 2008) who found that the aberration controlled contact lens reduced the SA or tended to over-correct SA. This result indicates that the lens had the effect as expected i.e., to change the SA. Measurements of accommodation showed no significant differences in time, velocity and/or lag of accommodation after decreasing the SA with the SACL in both monochromatic and polychromatic light. This indicates that SA and CA are not strong directional cues to accommodation, at least when accommodation is changed in large steps, as done in this study. These results are in line with Troelstra et al. (1964) who found that SA and CA were not important in determining the initial direction of accommodation. Further, other studies have also found similar results (Atchison et al., 1995b; He et al., 2005). On the other hand, this is not in line with the recent results of Theagarayan et al. (2009), a possible explanation could be that they introduced a larger magnitude (much greater than that normally found in the human eye) of negative SA. Also, Aggarwala et al. (1995a,b) found that accommodation under monochromatic conditions was not as accurate as accommodation under chromatic conditions, which indicates the importance of CA as a cue for accommodation. The difference in our findings could be due to the use of step rather than oscillatory stimuli; as used by Aggarwala et al., (1995a). Another possible explanation could be due to the anticipation of accommodation during the measurements which could have caused them to forecast the amount they needed to accommodate. This means that the stimulus change could have been predictable in both magnitude and direction; however, in a prior pilot study we used randomly selected stimuli in 1.00D steps. We were not able to find any learning trend in the pilot study. These findings are in line with the study by Troelstra et al. (1964), who found that the average error is about 50% and that there was no indication of trends or learning.

Since SA is the optical effect of peripheral rays not coming to focus in the same point as central rays, it is difficult to see how this can directionally guide accommodation for a target that is 2.0D out of focus, since the SA refraction pattern is small and far out of focus. This might be why we and others have found no effect on accommodation when changing the amount of normal values of SA. Spherical aberration might rather be a cue for maintaining a steady state level of accommodation rather than directional cue for large changes in accommodation. It is therefore likely that the accommodative system uses other cues for directional control. Under monocular conditions, proximal information, i.e., monocular cues to distance such as parallax motion, perspective, overlap etc., are the most likely cues for directional control. Under binocular conditions, these monocular cues are combined with input from the vergence system, i.e., convergence accommodation cross-link information, to yield the directional cues to accommodation.

Even if this study had some limitations, we could not find any clinical implication of accommodative response when changing SA. I therefore find it clinically safe to fit the commercially SACL without concern of consequential accommodation problems. On the other hand, some subjects might benefit from these lenses, especially for night driving and very detailed visual tasks.

The aim of the study IV was to investigate accommodative behaviour in young adults and adolescents with normal accommodation, and in subjects with accommodative insufficiency, fitted with an aspheric multifocal contact lens, with a special focus on evaluating whether these lenses can be an alternative treatment for subjects with accommodative dysfunction such as AI. The main findings of the present study were that young subjects did not relax their accommodation when fitted with aspheric multifocal center distance contact lenses. This was shown by the lag being the same with and without the lens. This is similar to the findings made by Tarrant et al. (2008). The AI subjects showed the same trend by not taking advantage of the addition inherent in the lenses. This is surprising since their accommodative ability is reduced. The AI subjects are after all, somewhat able to accommodate and it might be that they do not take notice of reading addition incorporated in these lenses since it does not occupy the central visual field. The light from the more peripheral part of the contact lens will also strike the cones at an angle that is not along the cone axis and this effect, the Stiles-Crawford effect, has been shown to be important in accommodation (Fincham, 1951). This might explain why both the normal and AI subjects do not relax their accommodation in near vision while wearing these lenses.

Based on our findings, and despite the low number of AI subjects included, the aspheric contact lens used does not seem suitable to be fitted on young subjects with AI in order to reduce their accommodative load and consequently achieve the same treatment effect that reading spectacles have on AI (Brautaset et al., 2008; Wahlberg et al., 2010). However, a larger study should be conducted to fully evaluate this. Furthermore, it might be worthwhile to evaluate the effect on accommodation with an aspheric multifocal centre near lenses in both normal subjects and subjects with accommodative dysfunction, since the subjects would then need to use the more peripheral part of the lens to see clearly at distance and the reading addition would occupy the central part of the visual field.
In conclusion from study IV, young normal subjects and young subjects with AI do not relax accommodation when fitted with aspheric multifocal centre distance lenses when the add is +1.00D. It is therefore unlikely that subjects with AI can be effectively treated with such lenses.

What was noticed while doing this experiment is that the amount of SA in the AI group seems to be higher than in normal subjects. To value these finding to a normal group in the same age, aberration measurement was also done on 18 children with a mean age of 10.1 (±0.32 SD) years, who showed a lower SA than the AI group. Supplementary studies have been undertaken to evaluate this further and to investigate whether this might be a possible cause of AI. With a high level of SA, the need for accommodation will be lower and it might be that this has made their accommodative system passive. On the other hand, this should not be the case if the Stiles-Crawford effect is essential in accommodation. Then it might just be a random finding that the AI subjects had higher values of SA.

2.4 CLINICAL GUIDELINES

Based on the findings in my studies, I would like to give the following clinical recommendations:

- Subjects with AI can be treated with either +1.00D reading addition or orthoptic exercises. The treatment chosen should be based on the willingness of the patient.

- When treating AI subjects, it is likely that the best possible effect will be gained if reading addition and exercises are combined.

- Reading addition should be kept low, about +1.00D, in order to achieve the best effect.

- Contact lenses that correct for spherical aberration have little, if any, effect on accommodation and can therefore be fitted without worrying about the effect they might have on accommodation.

- Multifocal contact lenses, at least with a center distance design, should not be prescribed as treatment for accommodative insufficiency.

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