Study of the dynamic interactions between vergence and accommodation

by

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Abstract

Introduction

Accommodation (change in ocular focus) and Vergence (change in ocular alignment) are two ocular motor systems that interact with each other to provide clear single binocular vision. While retinal blur drives accommodation as a reflex, retinal disparity changes accommodative position through the convergence-accommodation (or simply vergence-accommodation, VA) cross-link. Similarly, while retinal disparity primarily drives the vergence system, a change in retinal blur alters vergence through the accommodative-convergence (AC) cross-link. Although much information is known on the individual response dynamics of blur accommodation and disparity vergence, very little is known about the cross-linkages AC and VA. VA represents the unique situation where a stimulus to vergence (retinal disparity) drives a change in accommodation. When these dynamic measures are compared to those of vergence and blur accommodation a better understanding of the critical or rate limiting step within the system of vergence and accommodation can be determined. Accordingly, the purpose of this thesis was to determine the response dynamics of vergence driven accommodation (VA) and compare the response parameters to simultaneous measures of disparity vergence and blur driven accommodation.

Methods

A disparity stimulus generator (DSG) was modified to allow step stimulus demands of disparity to be created on a 0.2 cpd non-accommodative difference of Gaussian target. Retinal disparity of different step amplitude demands were created as an ON / OFF paradigm and projected on a stereo monitor set at a distance of 1.2m. Two experiments

were conducted. The first experiment investigated the first order properties of VA in comparison to similar measures of blur driven accommodation (BA). The second study aimed at comparing the first order and second order dynamics of disparity vergence, VA and BA.

In the first experiment, stimulus measures of vergence, vergence-accommodation and BA were studied. Six normal young adult subjects participated in the study. Accommodation was measured continuously at 25Hz with the commercially available PowerRefractor (Multichannel systems, Germany). A Badal optical system was designed and accommodative response to step stimulus demands were measured. VA and BA measures obtained from the PowerRefractor were matched and plotted as main sequences (amplitude vs. peak velocity). Peak velocities between the two responses were compared using two-way analysis of variance (ANOVA) with Bonferroni post-tests.

In the second experiment, the response dynamics of vergence, vergence-accommodation, and blur accommodation were assessed and compared on 6 young adult subjects. Eye position was measured continuously by a stereo eye tracker at a sampling rate of 120Hz. A high speed photorefractor (sampling = 60Hz) was custom designed and synchronized with a stereo eye tracker to allow simultaneous measurement of vergence and VA. Monocular blur driven accommodation measures were also obtained with the Badal optometer and the high speed photorefractor (sampling = 75Hz). VA, BA and disparity vergence responses were analyzed and temporal parameters like latency, amplitude, duration, time to peak velocity, peak acceleration, duration of acceleration, and skewness

were calculated. Main sequence plots (response amplitude vs. peak velocity) were generated and compared between disparity ON and disparity OFF. The dynamic measures of VA were compared to the measures of monocular blur driven accommodation. All comparisons were done using a two-way ANOVA with Bonferroni post-tests.

Results

Study 1: The results showed that response amplitude of VA during disparity ON and disparity OFF paradigms was linearly related to the peak velocity for an amplitude range of 0.5 to 2.5 D (Disparity ON: peak velocity of vergence-accommodation = 0.812 * amplitude + 1.564, R^2 = 0.452, p<0.0001 and Disparity OFF: peak velocity of vergence-accommodation = 1.699* amplitude – 0.234, R^2 = 0.86, p <0.0001). The rate of change of peak velocity as a function of response magnitude was lower for VA during disparity ON compared to VA during disparity OFF. BA responses also showed amplitude dependent dynamic properties (Accommodation peak velocity = 1.593 * amplitude - 0.008, R^2 = 0.84, p<0.001; Dis-accommodation peak velocity = 1.646 * amplitude - 0.036, R^2 = 0.77, p<0.001). There was no statistical difference in the velocity of accommodation and dis-accommodation.

Study 2: When amplitudes were matched, disparity vergence response during disparity ON and disparity OFF had similar main sequence relationships. The mean values for the stimulus and response VA/V ratios were similar (0.13±0.05 D/Δ and 0.15±0.09 D/Δ respectively). All the temporal parameters of vergence-accommodation were similar

during disparity ON and disparity OFF paradigms. When blur accommodation and vergence-accommodation measures were compared, all the first order and second order temporal parameters in the response were similar between the two systems. Also, disparity vergence exhibited significantly greater peak velocity and peak acceleration compared to two accommodation responses. The results also confirmed that the velocity of accommodation and dis-accommodation showed a statistically significant linear relationship as a function of amplitude for the range of amplitudes tested (Accommodation, $y = 2.55x + 0.65$, $R^2 = 0.55$, $p<0.0001$; Dis-accommodation, $y = 2.66x + 0.50$, $R^2=0.65$, $p<0.0001$).

Conclusions

The dynamic properties of VA are amplitude dependent. Although initial results from study 1 suggested that VA may be slower during disparity ON, the results from study 2 using the high speed photorefractor and an improved analysis procedure showed that VA responses were equally fast between disparity ON (convergence) and disparity OFF (divergence). All temporal properties of VA were independent of vergence type (convergence/divergence). VA and BA have similar dynamic properties in humans suggesting that they may controlled by a common neural pathway or limited by the plant. Also, when compared to accommodation responses, disparity vergence exhibited greater velocities and accelerations reflecting the differences in the magnitude of neural innervation and plant mechanics between the two systems. The study also confirmed amplitude dependent response dynamics of blur driven accommodation and dis-accommodation.

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Dedication

To my parents, brothers & family and my wife Subha

for their unflinching love and support

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1 *Review of Human Accommodation and Vergence*

1.1 Accommodation and Vergence

Accommodation is the process by which changes in the dioptric power of the crystalline lens cause a focussed image to be formed at the fovea (Ciuffreda, 1991). Although the primary stimulus for accommodation has been recognised to be retinal blur (Phillips & Stark, 1977), accommodation has also been shown to be elicited in response to retinal disparity (Fincham & Walton, 1957), proximal stimuli (Hofstetter, 1942; Hokoda & Ciuffreda, 1983) and tonic position (Leibowitz & Owens, 1978). Stimulus to accommodation refers to the theoretical (assumed) demand of accommodation and is derived as the dioptric equivalent of the object fixated in meters. Response accommodation, on the other hand, refers to the actual amount of accommodation exerted by the eye. The mechanism of accommodation has been of interest for more than a century now and numerous investigations have attempted to outline its static and dynamic properties.

Vergence can be defined as the movement of two eyes in opposite directions (Westheimer & Mitchell, 1956; Westheimer & Mitchell, 1969). Although the primary stimulus for vergence is retinal disparity (Stark, Kenyon, Krishnan, & Ciuffreda, 1980), vergence is also elicited in response to proximal cues (Hokoda & Ciuffreda, 1983), changes in tonic innervation (Owens & Leibowitz, 1983) and through the synkinetic link from accommodation (Alpern & Ellen, 1956). A vergence eye movement towards the midline (convergence) occurs in response to crossed retinal disparity whereas a

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movement of the two eyes away from the midline (divergence) occurs for uncrossed disparities. The vergence system has been thought to be composed of four components namely, accommodative (driven by retinal blur as a synkinetic response from accommodation system), fusional (also known as disparity vergence), tonic (resting state of the eye) and proximal (awareness of a near object) (Maddox, 1893; Morgan, 1980).

Although ocular motor systems have been effectively classified into different subgroups, it is important to note that cross-coupling between the subgroups has been an important means through which accurate responses in monocular and binocular vision is achieved. Examples of such cross-linkages include the cross-talk between saccade-vergence (Zee, Fitzgibbon, & Optican, 1992), horizontal-vertical vergence (Schor, Maxwell, McCandless, & Graf, 2002) and accommodation-vergence (Alpern & Ellen, 1956; Fincham & Walton, 1957). Of these cross-linkages the coupling between accommodation and vergence is the most well known. Under normal binocular viewing conditions, accommodation and vergence interact with each other through reciprocal cross-link interactions where optically stimulated accommodation evokes convergence (Alpern & Ellen, 1956) and disparity stimulated vergence evokes accommodation (Fincham & Walton, 1957). The magnitudes of these interactions are quantified as AC/A (ratio of accommodative convergence to accommodation) and CA/C (ratio of convergence induced accommodation to convergence).

1.1.1 Static properties of accommodation, vergence and cross-linkages

1.1.1.1 Static aspects of accommodation

The stimulus-response curve has been the classical method for describing the relationship between stimulus and response accommodation (Morgan, 1944a; Morgan, 1944b; Morgan, 1968). When accommodative response is plotted as a function of stimulus three discrete intervals are found. An accommodative lead (accommodative response > accommodative stimulus demand) for lower stimulus levels, lag (accommodative response < accommodative stimulus demand) at intermediate stimulus levels and a saturation of response at higher stimulus demands indicating that the maximum amplitude of accommodation has been reached (Morgan, 1968). The slope of the stimulus-response curve at the intermediate stimulus levels is less than unity (0.91) for young adults (McBrien & Millodot, 1986). With presbyopia, the effective linear range of the curve gets shorter as the amplitude of available accommodation decreases (Hamasaki, Ong, & Marg, 1956). Pupil size also acts as a strong influencing factor for accommodation since a decrease in pupil size would increase the depth of focus which in turn might reduce the actual accommodative response (Ward & Charman, 1985).

1.1.1.2 Static aspects of Vergence

The difference between stimulus and response vergence is known as fixation disparity (Ogle, 1954) and is considered as the steady state error of the vergence system. Fixation disparity errors are small in magnitude, usually within 2' of arc indicating that the responses of the vergence system are very accurate (Ogle, 1954). Fixation disparity has

traditionally been measured with forced vergence stimuli where accommodation and vergence cues were both active (Saladin & Sheedy, 1978; Sheedy, 1980). However, when the stimulus to accommodation was removed and the focussing system was made open-loop, fixation disparity errors were found to decrease by a factor of one-half. This showed that the accommodative contribution to fixation disparity was more than the contribution of disparity alone (Semmlow & Hung, 1979).

1.1.1.3 Crosslink interactions AC and CA

Accommodative convergence (AC) was first described by Johannes Muller about two centuries ago (1843). When a negative lens was placed in front of one eye while the other eye was occluded, the occluded eye converged by an amount that was linearly related to the amount of accommodation exerted (Muller, 1843). The measurement of AC required that the vergence system be open-loop (disparity information removed) by occluding one eye while a strong stimulus to accommodation prevailed. The clinical measure of this cross-link, the AC/A ratio is known to be 4±2 Δ/D in normal subjects (Alpern & Ellen, 1956). The AC/A ratio was shown to be higher by 8% when response accommodation is measured instead of the calculated stimulus measures (Alpern, Kincaid, & Lubeck, 1959).

Convergence-accommodation (CA) was first described by Fincham and Walton (1957) as reciprocal actions of vergence and accommodation. Since then, its static properties have been studied by a number of investigations (Fincham & Walton, 1957; Kent, 1958; Kersten & Legge, 1983; Tsuetaki & Schor, 1987; Rosenfield & Gilmartin, 1988; Wick & Currie, 1990; Bruce, Atchison, & Bhoola, 1995). The CA cross-link is measured by

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rendering blur driven accommodation open-loop while maintaining a strong stimulus for vergence. For example, the CA cross-link could be measured by viewing through binocular pinholes (0.5mm or less) while a vergence demand is created by a prism placed before one eye. The resulting change in vergence drives accommodation which can be measured as CA. A variety of methods have been used to measure the CA cross link gain and the results have been found to range from 0.04 – 0.22 D/Δ. The ratio has also been shown to correlate negatively with age (Fincham & Walton, 1957; Bruce, Atchison, & Bhoola, 1995; Rosenfield, Ciuffreda, & Chen, 1995; Heron, Charman, & Schor, 2001b) and positively with available amplitude of accommodation (Wick & Currie, 1990; Bruce, Atchison, & Bhoola, 1995). The cross-link CA/C can be represented as a stimulus measure where the vergence demand is set as a function of the stimulus to vergence or defined as a response measure where the actual amount of vergence response is measured. Given the accurate dynamics of disparity vergence the differences between the stimulus and response CA/C ratios would be expected to be small.

1.2   Basic model of Accommodation and Vergence

1.2.1   Static model of accommodation and vergence

Accommodation and Vergence have been described by mathematical models that define the functions of the two systems within a feed-back driven closed loop system (Hung & Semmlow, 1980). A schematic of the accommodation-vergence model is shown in **Figure 1.1.**
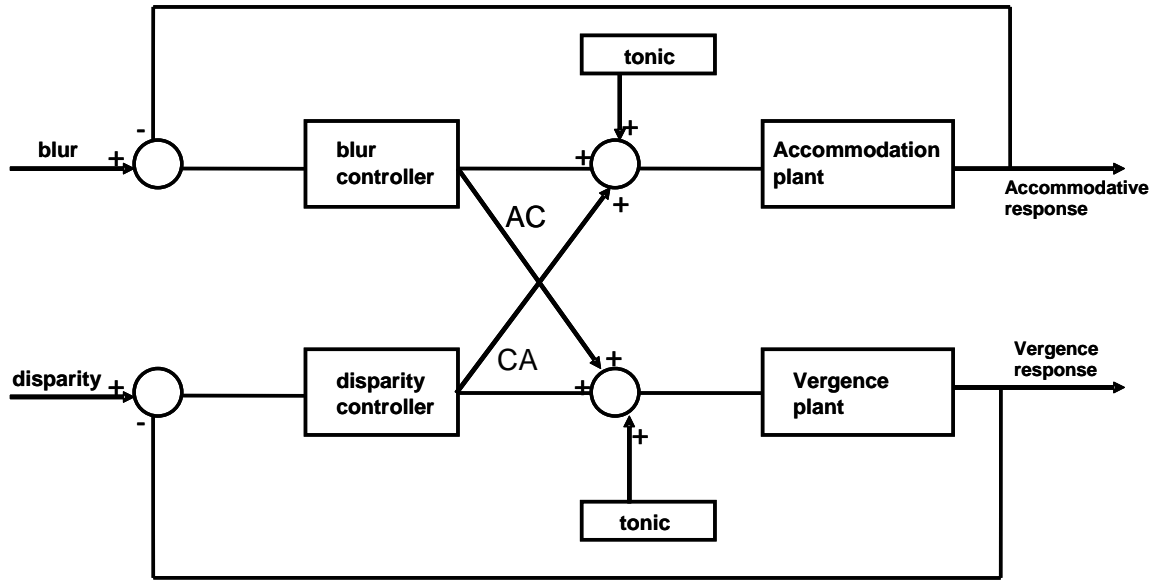
Figure 1.1 Negative feedback model of accommodation and vergence showing cross-link interactions AC and CA.
Under normal binocular viewing conditions both systems are closed loop and negative feedback is operational. Adapted from Hung & Semmlow, 1980

The model typically shows two parallel systems that interact with each other through cross-links accommodative-vergence (AC) and convergence-accommodation (CA). Each system is represented as being composed of different components namely the controller, cross-links, tonic input and plant. The response of each system is affected by the output of each of the individual components. The controller block has two actions. First, it responds as a reflex to any stimulus presented through the loop and secondly, it feeds in as the input to the cross-links AC and CA. Finally the responses of each system are summed up at a summing junction where tonic input feeds in. The resultant response of each system is directed to a plant mechanism (a structure receiving innervation), which symbolizes the extra ocular muscles for vergence and the ciliary muscle, crystalline lens, zonules for accommodation. The error (stimulus - response) is fed back into the system as

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negative feedback to maintain the responses and keep it stable. This negative feedback is characteristic of ocular motor systems (Leigh & Zee, 1991b).

1.2.2   Plant mechanics of accommodation and vergence

1.2.2.1 Extraocular muscles

The plant or the physiological structure receives the neural signal and executes the motor response (Quaia & Optican, 2003). The extraocular muscles are unique in that they co-ordinate a spectrum of eye movements ranging from slow to fast resulting in precise alignment of the eyes within a very narrow threshold so that double vision is not experienced. Each eye is rotated by six extraocular muscles (4 recti, namely superior, inferior, medial, lateral recti and 2 obliques, namely superior, inferior) and the way in which these extraocular muscles produce eye movements is complicated (Demer, 2003;Demer, 2004). Each muscle can be thought to rotate the eye in all three directions (X, Y and Z) (Nakayama, 1983). The superior, inferior, medial recti and inferior oblique are innervated by the oculomotor nerve whereas the lateral rectus and superior oblique are innervated by the abducens nerve and trochlear nerve respectively. Six distinct muscle fibre types have been identified in the EOMs (Porter, Francisco, & Baker, 2002). Although earlier concepts suggested that each muscle fibre type may be associated with a particular type of eye movement, electromyographic studies showed that all muscle fibre types participate in all classes of eye movements (Scott & Collins, 1973). The muscle fibres differ in terms of the size of the myofibril, number and size of mitochondria, energy metabolism, contraction mode (fast twitch, slow tonic and mixed) and fatigue resistance (high, moderate, intermediate, slow and poor) (Spencer & Porter, 1988). The

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muscle fibres of the EOMs are among the fastest contracting in the body and they are also known to be relatively fatigue resistant (Leigh & Zee, 1991a; Porter, Francisco, & Baker, 2002).

1.2.2.2 Ciliary muscle, Crystalline lens and zonules

The plant mechanics for the accommodation system consists of the ciliary muscle, crystalline lens and zonules. The ciliary muscle is a smooth muscle that is responsible to bring about the accommodative response. The ciliary muscle is also unique in that it has both parasympathetic and sympathetic innervations. The parasympathetic innervation is mediated by the muscarinic receptors (Gilmartin, 1986) and the sympathetic innervation is mediated by β-adrenergic receptors (Chen, Schmid, & Brown, 2003; Mallen, Gilmartin, & Wolffsohn, 2005). The ciliary muscle has been suggested to be atypical for smooth muscles in its speed of contraction, the larger size of its motoneurons, the distance between the muscle and the motoneurons and the unusual ultrastructure of the ciliary muscle cells which resemble that of skeletal muscle (Glasser & Kaufman, 2002). The ciliary muscle is composed of three different muscle fibres namely the longitudinal, radial and circular fibres. Contraction of the ciliary muscle results in contraction of all three muscle fibres and primarily serves to reduce the resting tension on the zonules (Tamm & Lutjen-Drecoll, 1996).

When the eye is focussed at distance, the resting tension of the zonules holds the crystalline lens in its un-accommodated state. During the act of accommodation, the ciliary muscle contracts, the apex of the ciliary muscle moves forward to relieve the

resting tension on the zonules. With the release of the force on the crystalline lens, the lens capsule molds the lens substance into a more spherical accommodated form. The lens diameter increases and the radius of curvature of the anterior and posterior surfaces of the lens change with accommodation. The anterior surface becomes more convex during accommodation compared to the posterior surface. This causes an increase in the optical power of the lens (Helmholtz theory of accommodation summarized by Gullstrand, 1962; see Glasser & Kaufman, 1999 for review). During dis-accommodation, the elastic properties of the choroid pulls the ciliary muscle back to its initial position, restores the tension on the zonules and brings the crystalline lens to its original form (Glasser & Kaufman, 2002).

The motor innervation to accommodation is supplied primarily by the parasympathetic component. Initial studies on animal models suggested that the motor innervation of accommodation may be direct without a synapse at the ciliary ganglion (Westheimer & Blair, 1973). Anatomical evidence challenged this finding suggesting that the accommodation pathway may not be direct and may indeed synapse at the ciliary ganglion (Ruskell & Griffiths, 1979; Ruskell, 1990). Although the innervation to the accommodation system is considered to be primarily parasympathetic, a review of the previous literature (Gilmartin, 1986; Gilmartin, Mallen, & Wolffsohn, 2002; Chen, Schmid, & Brown, 2003) shows anatomical and pharmacological evidence that suggest a dual innervation model where parasympathetic (muscarinic) and sympathetic (β-adrenergic) divisions initiate specific accommodative responses. The features of the sympathetic input have been suggested to be primarily inhibitory, relatively small in

magnitude (<-2D) and have a slower time course (20 – 40 secs compared to 1 – 2 secs for the parasympathetic system) (Rosenfield & Gilmartin, 1989).

1.2.3 Dynamic properties

One of the methods to identify and differentiate a given ocular motor response (example accommodation vs vergence) has been the study of its dynamic or time varying properties. Several parameters can be defined and studied by examining the time varying properties of the response. Such measures provide an insight into the neural basis of the response. Furthermore, if normal response dynamics are well known, it will help in the identification of abnormal responses that may occur due to pathology or other reasons. In the case of cross-links between accommodation and vergence, dynamic measures will provide fundamental information on how complex responses are modified.

1.2.3.1 General Definitions in ocular motor systems

Figure 1.2 shows an example of a typical response to a step stimulus demand input. Several response parameters can be defined from this figure. The time interval between the start of the stimulus and start of the response is defined as the latency (reaction time) of the response. The time interval between the start and end of the response is referred to the movement time (response duration). Amplitude is defined as the absolute difference in the position of the response between its start and end.
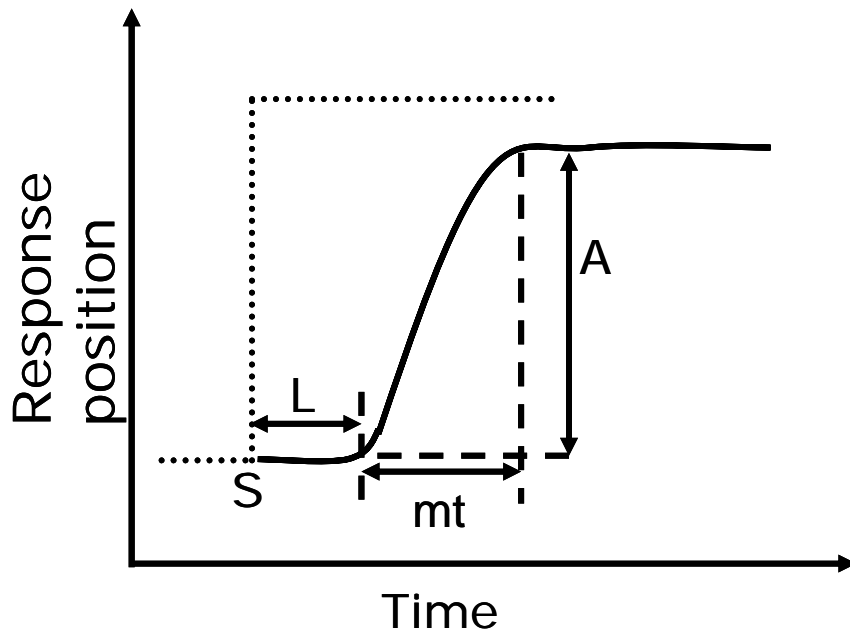
Figure 1.2 Definition of the dynamic parameters in a response.
Stimulus (dotted line) is presented at time S and response occurs after a brief latency (L). The response (solid line) has a duration (mt) and an amplitude defined by A.

While some of the parameters can be defined from the response position, others are defined based on their velocity profiles. The velocity profiles are acquired by differentiating the position traces. From the velocity trace, the highest value on the velocity profile is defined as the peak velocity. The time to peak velocity is defined as the time taken to change from 0 D/s to peak velocity.

1.2.3.2 Main sequence

One of the characteristic plots that can be derived from these dynamic parameters is the main sequence. The main sequence is a plot of the peak velocity as a function of response amplitude. The main sequence was first used in the field of astronomy to relate the luminosity – mass relationship of stars and was later adapted to ocular motor research. The main sequence was first described for the saccadic ocular motor system (Bahil,

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Clark, & Stark, 1975). This method of analysis provides an understanding of how the dynamic properties of the response change with increasing amplitude. The main sequence has been used to understand the neural generation of saccades and also to identify abnormal saccades (Leigh & Kennard, 2003). The duration of the saccades is also known to be directly related to their amplitude and this relationship has been shown to be linear for saccades up to about 50 degrees (Carpenter, 1977).

1.2.4   Dynamics of disparity vergence

1.2.4.1 General Dynamics

The disparity vergence response exhibits a latency of 130 – 250 msecs and a total response time of about 1 sec (Rashbass & Westheimer, 1961; Krishnan, Farazian, & Stark, 1973; Semmlow & Wetzel, 1979; Hung, Zhu, & Ciuffreda, 1997; Heron, Charman, & Schor, 2001b) . Children (4.5 – 12 yrs) have been shown to have a longer and more variable latencies for disparity vergence compared to adults (Yang, Bucci, & Kapoula, 2002). The magnitude of the latency reached adult levels at approximately 10 – 12 years of age. Disparity vergence measures recorded on adults (16 – 48 years) have shown that when modest stimulus demands are used (6Δ), most of the temporal parameters (latency, maximal velocity, response time) for the vergence system remained constant (Heron, Charman, & Schor, 2001b).

1.2.4.2 Comparison between convergence and divergence

The dynamics of convergence and divergence have been compared as well. However, the results have been contradictory so far no clear relationship has been determined. In some cases convergence was reported to be faster than divergence (Zee, Fitzgibbon, & Optican, 1992; Hung, Ciuffreda, Semmlow, & Horng, 1994; Hung, Zhu, & Ciuffreda, 1997) while other investigations report similar velocities for convergence and divergence (Collewijn, Erkelens, & Steinman, 1995). A comprehensive analysis of various temporal parameters (latency, time to peak velocity, time constant, total duration and main sequence analysis) was provided by Hung et al. (1997) who studied symmetric convergence and divergence responses for five different stimulus demands (2, 4, 8, 12 and 16 degrees). The stimulus demands always started from the same baseline position and changed to crossed disparities for convergence and uncrossed disparities for divergence. The results from Hung et al. (1997) showed that latency, time to peak velocity and time constant were all shorter for convergence compared to divergence. These differences were statistically significant when cumulatively compared over the full range of amplitudes. Main sequence analysis (response amplitude vs. peak velocity) showed that the slope of the linear portion of the main sequence was steeper during convergence (slope for convergence was approx = 4 and slope for divergence was approximately = 2). Overall, this showed that the dynamic properties of convergence were faster compared to divergence.

1.2.4.3 Vergence dynamics as a function of starting position

Recently, it has been suggested that the dynamics of convergence and divergence differ as a function of the initial starting position (Alvarez, Semmlow, & Pedrono, 2005). Alvarez et al. (2005) studied 4 subjects and vergence responses were recorded with an infrared limbal eye tracker while disparity changed as step amplitude of 4 degrees from different initial starting positions. The results of the study showed that when responses started at initial starting positions of 16 to 20 degrees, convergence and divergence had similar peak velocities (convergence: 18.07±4.88 deg/s and divergence: 19.36±4.6 deg/s). However when responses started at initial starting positions of 4 to 8 degrees, convergence was approximately twice as fast as divergence (convergence: 20.82±3.82 deg/s and divergence: 8.08±1.37 deg/s). These results suggest that divergence gets faster and more equal to convergence if initial starting positions are more proximal to the subject. Thus, the discrepancies between convergence and divergence may relate to the dependency of the dynamic measures on the proximity of the target.

1.2.4.4 Disparity vergence and accommodative vergence

Although disparity vergence and accommodative vergence have been studied individually, only a few studies have provided information about both these parameters on the same subjects (Semmlow & Wetzel, 1979; Heron, Charman, & Schor, 2001b). Semmlow and Wetzel (1979) studied vergence responses to randomly occurring steps of fusional and accommodative stimulation in two separate experimental runs on five subjects between 18 – 30 yrs of age. Stimulus amplitudes were 1.5 to 2.5 D for

accommodative vergence (AV) and 1.5 to 2.5 MA for fusional vergence (FV). The results showed that with the exception of one subject, fusional vergence had latencies that were 70 to 250 msecs shorter and time constants that were 90 – 900 msecs shorter compared to accommodative vergence. The study also compared the dynamics of the vergence movements produced by a step change in accommodative + fusional stimulus levels and fusional step stimulation only. The results showed that in normal binocular vergence, the initial portion of the movement would be largely due to fusional stimuluation with the accommodation component contributing only in the final portion of the response. However, when statistical significance (paired t-test) was estimated from the data provided by Semmlow and Wetzel (1979) it was found that for positive (increasing) stimuli, the latency and time constant of AV and FV were significantly different (latency $p=0.007$, time constant $p=0.045$). On the other hand, for negative (decreasing) stimuli both latency and time constants were not statistically different between AV and FV. Hence the results of Semmlow and Wetzel (1979) do not provide strong evidence to support the suggestion that the dynamics of AV and FV may be different.

A recent study by Heron et al. (2001) on 13 subjects between 16 to 48 years of age showed that the latency and response duration of disparity vergence (convergence and divergence demands of 6Δ) were shorter than accommodative vergence (increasing and decreasing accommodation of ±2 D). Overall (for both increasing and decreasing demands) the results showed that disparity vergence had latencies that were 18 to 50 msecs shorter and response durations that were 300 to 1100 msecs shorter than accommodative vergence. However, the study reported no statistical comparisons

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between the response dynamics of accommodative vergence and fusional vergence. In summary, the results obtained from Semmlow and Wetzel (1979) and Heron et al. (2001) do not provide a strong evidence to prove that AV may have longer response dynamics compared to disparity vergence.

1.2.5   Dynamics of blur driven accommodation

1.2.5.1 General Dynamics

Accommodative responses show a latency of approx 350 – 500 msecs and a total response time (latency + movement time) of about 1 sec (Campbell & Westheimer, 1960;Phillips, Shirachi, & Stark, 1972; Shirachi, Liu, Lee, Jang, Wong, & Starks, 1978; Tucker & Charman, 1979; Sun & Stark, 1986; Sun, Stark, Nguyen, Wong, Lakshminarayanan, & Mueller, 1988; Heron & Winn, 1989; see Hung, Ciuffreda, Khosroyani, & Jiang, 2002 for a review). Individual results for the temporal parameters show a wide range of values between the studies. Accommodation dynamics have been studied across different age groups and results from these investigations have been variable. While some results showed a decrease in speed of response with age (Allen, 1956; Fukuda, kanada, & Saito, 1990; Schaeffel, Wilhelm, & Zrenner, 1993; Beers & Van der Heijde, 1996), others showed no change in near to far (Temme & Morris, 1989) or far to near accommodation (Heron & Winn, 1989). The main differences between the studies were the age range of the sample, instrumentation, the choice of the stimulus demand and the relative position of that demand within the linear portion of the accommodative stimulus-response curve. The latter was clarified by showing that if

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stimulus demands were well within the individual's amplitude of accommodation (linear portion of their stimulus-response curve), the dynamic properties (latency, response time, time constant, peak velocity) of the resulting accommodative response remained constant when tested in adults between 16 and 48 years of age (Heron, Charman, & Schor, 2001a; Mordi & Ciuffreda, 2004).

1.2.5.2 Main sequence of accommodation

Accommodation dynamics have also been studied in terms of the main sequence. The first study to report on the main sequence of accommodation showed that the relationship between accommodative response amplitude and peak velocity was linear for response amplitudes up to 3D (Ciuffreda & Kruger, 1988). The results showed that, qualitatively, all types of accommodative response (normal reflex, fast reflex, and voluntary accommodation) have similar and overlapping linear main sequence functions. Accommodation driven by a voluntary effort (analogous to an open-loop situation) was found to have similar dynamic properties in comparison to normal reflex accommodation (Ciuffreda & Kruger, 1988).

Recently, many investigations have reported on main sequence of accommodation in humans (Kasthurirangan, Vilupuru, & Glasser, 2003; Mordi & Ciuffreda, 2004; Bharadwaj & Schor, 2004) and monkeys (Vilupuru & Glasser, 2002). While results on monkeys show a linear change in their main sequence over the full range of amplitudes (0 to 18D), results on humans (young adults) have shown considerable variability and no clear relationship when tested over a wide range of amplitudes (0 – 8D) (Kasthurirangan,

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Vilupuru, & Glasser, 2003). However, the amplitude vs. peak velocity plot was linear and less variable for a smaller amplitude range (Bharadwaj & Schor, 2004, Mordi & Ciuffreda, 2004) on a similar age group (20 – 30 years).

When the stimulus demand used was well within the individual's amplitude of accommodation or the linear portion of their stimulus-response curve, the slope of the linear portion of the main sequence was similar in adults between 21 to 50 years (Mordi & Ciuffreda, 2004). These results agree well with similar investigations on other temporal parameters (latency, duration, time constant) of accommodation discussed earlier (Heron, Charman, & Gray, 1999; Heron, Charman, & Schor, 2001a; Heron, Charman, & Schor, 2001b; Heron, Charman, & Gray, 2002; Heron & Charman, 2004). Cumulatively, the investigations suggest that accommodation dynamics do not appear to change in adults (21 – 50 years) for modest stimulus amplitudes that are well within the actual available amplitude of accommodation.

1.2.5.3 Second order dynamics and pulse step control of accommodation

While main sequence investigations reported on the first order dynamics (velocity) of accommodation, it was recognized recently that some of the dynamic features of the response might be missed if the investigations were only limited to first order analysis (Alvarez, Semmlow, Yuan, & Munoz, 1999). The study results of Alvarez et al. (1999) suggested that for a comprehensive assessment of response dynamics it would be necessary to investigate the higher order dynamic properties of the response as well. Accordingly, a recent study (Bharadwaj & Schor, 2004) explored both the first order and second order properties of the response accommodation. Six young adult subjects were

studied and dynamic accommodative responses to step stimulus demands (1 – 4D range) were recorded. First order (velocity) and second order (acceleration) parameters were computed from the accommodation traces and several temporal parameters (response amplitude, peak velocity, peak acceleration, time to peak acceleration and duration of acceleration) were analyzed. The results of the study showed that peak velocity of accommodation changed significantly with response magnitude (slope of the linear portion of the main sequence ranged from 0.72 to 1.76). For the second order dynamics, the mean value of the peak acceleration and time to peak acceleration varied from 44.5 to 89.9 D/s^2 and 83 to 120 msecs respectively. Neither of these parameters changed significantly with response magnitude. On the other hand, when response amplitude was plotted against the total duration of acceleration, a moderate correlation was found. Linear regression analysis (amplitude vs. duration of acceleration) showed that the slope was statistically significant (slope of the linear regression ranged from 24.03 to 41.8 msecs/D). These results collectively suggested that the peak velocity of accommodation is achieved by increasing the total duration of acceleration instead of increasing the amplitude of acceleration. These results also led the authors to suggest a dual-innervation input to the accommodation system with an initial open-loop component that is invariant with response magnitude coupled with a closed-loop innervation that correlates with a change in response magnitude (Bharadwaj & Schor, 2004). The empirical responses obtained from their study were also mathematically described as a two component pulse-step model where a fixed height variable width acceleration pulse is integrated with a variable height velocity step to form a combined phasic-tonic signal for accommodation (Schor & Bharadwaj, 2005).

1.2.5.4 Accommodation vs. Dis-accommodation

Dis-accommodation or near to far accommodation can be defined as the decrease in accommodation following the withdrawal of the step stimulus. Few studies have investigated the dynamics of dis-accommodation (Temme & Morris, 1989; Sun, Stark, Nguyen, Wong, Lakshminarayanan, & Mueller, 1988; Schaeffel, Wilhelm, & Zrenner, 1993). Of these studies, Schaeffel et al. (1993) provided a comprehensive analysis of both accommodation and dis-accommodation on a wide age range of subjects. Schaeffel et al. (1993) studied 39 subjects between the ages of 5 and 49 yrs and recorded their accommodative response using a custom designed photorefractor while the subjects accommodated and dis-accommodated to a 4D stimulus demand. The speed of accommodation (far to near) and dis-accommodation (near to far) was measured and the differences between them were ranked. The results showed that in 29 out of 39 subjects, dis-accommodation was faster than accommodation. The results also showed that both measures had significant inter-individual variability. A few recent studies have further investigated the dynamic properties of the dis-accommodative response in humans (Heron, Charman, & Schor, 2001a; Kasthurirangan, Vilupuru, & Glasser, 2003; Bharadwaj & Schor, 2003) and monkeys (Vilupuru & Glasser, 2002) and extended the analysis in terms of main sequence. When the results from all the above investigations are compared several important features are evident.

Results on monkeys showed that, similar to accommodation, the amplitude-velocity relationship of dis-accommodation was linear over the entire range of amplitudes tested. The slope of the linear regression for accommodation and dis-accommodation were 2.439

and 6.901 respectively. The slope for dis-accommodation was 2.8 times steeper than for accommodation. Dis-accommodation was clearly faster than accommodation over the full range of amplitudes tested (Vilupuru & Glasser, 2002).

In human subjects, dis-accommodation also showed different dynamic properties compared to accommodation. When modest stimulus amplitudes (±0.75 and ±1.75) were tested, mean velocity and peak velocity were both found to be faster for dis-accommodation compared to accommodation. This effect prevailed regardless of age and applied for both young (16 -26 yrs) and older (36 – 48 yrs) subjects (Heron, Charman, & Schor, 2001a). A plot of the amplitude vs. peak velocity showed dis-accommodation to be linear (slope = 4.18) for the entire range of response amplitudes whereas accommodation showed significant inter-individual variability and no clear relationship (Kasthurirangan, Vilupuru, & Glasser, 2003).

Another important characteristic of dis-accommodation was its dependency on '*initial starting position*'. Dis-accommodation responses that started at different initial positions and ended at the same final position (example 1.5 to 0, 2 to 0, 2.5 to 0) showed peak velocities that correlated strongly with response magnitude [slope = 3.65, p<0.05] and dis-accommodation that started at the same initial position but ended at different final positions showed peak velocities that were constant with response magnitude [slope = 0.67, p>0.05] (Kasthurirangan & Glasser, 2003). The results from the same study also showed that main sequence ratio (slope of the linear portion of the main sequence function) was more variable when dis-accommodation started at different initial

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positions. A recent study (Bharadwaj & Schor, 2003) has also confirmed this finding by investigating first order and second order dynamics of dis-accommodation starting from a constant position of 6D. The dis-accommodative steps ranged from 1 – 4D and were presented monocularly. The results showed that the first order and second order parameters of dis-accommodation (peak velocity, time to peak velocity, time to peak acceleration, peak acceleration, and duration of acceleration) were all independent of response magnitude (Bharadwaj & Schor, 2003).

1.2.6 Dynamics of convergence accommodation

1.2.6.1 General Dynamics

Although considerable information is known about the static aspects of the CA cross-link, there is less information on its dynamic properties. Only a few studies have successfully measured the temporal properties of the CA response (Krishnan, Shirachi, & Stark, 1977; Heron, Charman, & Schor, 2001b; Suryakumar & Bobier, 2004).

Krishnan et al. (1977) published the first report on the dynamics of accommodation associated with disparity driven convergence and divergence. Dynamic parameters like latency and duration were studied on two adults. The results showed that convergence accommodation responses had a mean latency of 300 ± 200 msec and were completed after 1 second from the response onset. Krishnan et al. (1977) also provided information on one subject about divergence driven decrease in accommodation. The results showed that the duration of the response was 800 msec for far to near (convergent) stimuli and 1250 msecs for near to far (divergent) stimuli. Based on this subject's results the authors

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suggested that divergence driven dis-accommodation was slower and had longer latencies compared to convergence driven accommodation.

Heron et al. (2001b) evaluated the dynamics of CA on 13 adults (16 to 48 years of age) for modest disparity demands (6Δ) that were within the linear range of available vergence amplitude. Linear regression describing the change in the dynamic parameters of CA (y) vs. age (x) showed that most of the dynamic parameters remained constant (Latency: $y = 276+2.6x$, $p=0.63$; Response time: $y = 731 – 6x$, $p=0.52$; Mean velocity: $y = 2.6 – 0.032x$, $p=0.18$; Maximum velocity: $5.58 – 0.086x$, $p=0.004$).

A recent study (Suryakumar & Bobier, 2004) investigated the movement time of CA (time difference between the onset and completion of the CA response) and stimulus CA/C ratio on a sample of pre-school children and showed that the cross-link gain and the movement time of CA are not different between pre-school children and adults for modest disparity stimuli (movement time: child 787 ± 216 msecs, adult 743 ± 70 msecs, $p >0.05$).

Since convergence-accommodation would be expected to increase with convergence and decrease with divergence, it would be more appropriate to refer CA as vergence-accommodation (VA). Accordingly, throughout the rest of this thesis, CA cross link will be more generally referred to as vergence-accommodation or simply as VA. The CA/C cross-link ration will be referred to as the VA/V ratio.

1.2.6.2 Comparison to blur driven accommodation

One important feature that has received very little attention has been the comparison between vergence driven accommodation and monocular blur driven accommodation. As outlined earlier **(section 1.2.5)** many investigations either studied the accommodation driven by blur or the accommodation driven by disparity **(section 1.2.6)**. In order to compare the dynamics of vergence-accommodation and blur driven accommodation it would be necessary to investigate both these responses on the same individuals/animals.

So far only one study has investigated the dynamic properties of vergence accommodation and blur accommodation in the same individuals. Cumming and Judge (1986) investigated the dynamics of binocular vergence accommodation and monocular blur driven accommodation in two monkeys (maccaca mullata). Accommodation and vergence responses were recorded for a sinusoidally moving target (freq 0.1 – 1.2 Hz, peak to peak amplitude of 0.5 – 4 D / meter angles). Three different conditions were examined: monocular (open-loop vergence but closed loop accommodation), binocular (both accommodation and vergence closed loop), binocular viewing through pinholes (open-loop accommodation but closed loop vergence). The results showed that both accommodation and vergence velocities were higher during binocular viewing compared to monocular viewing with no differences between the monocular and binocular viewing for response latency. The accommodative response showed a lower phase lag and greater gain during binocular viewing compared to monocular. Furthermore, when vergence-accommodation responses (binocular viewing through pin holes) were compared to monocular blur driven accommodation, they found vergence-accommodation response to

have larger amplitudes (greater gain) and lower phase lags to sinusoidal stimuli. These results led the authors to conclude that the dynamic control of vergence and accommodation relied predominantly on disparity signals. However, a closer examination of the individual data between the two monkeys showed significant inter-sample variation. The reported differences in the phase lag between the two paradigms were not apparent at all frequencies and showed significant variation between the two monkeys tested. Also, the actual gain values vergence-accommodation and monocular accommodation were very similar. Hence, the results do not provide a strong evidence for the authors to claim that the dynamics of vergence-accommodation is superior when compared to that of blur.

1.2.6.3 The need for further investigation

Although comparisons between vergence-accommodation and blur accommodation have been attempted in monkeys, there have been no investigations on the comparisons between the two systems in human subjects (in the same individuals). Knowledge of the similarities / differences between vergence accommodation and blur accommodation is essential as it would help to outline the specific contributions of each of these systems to the net accommodative response. Most of the visual tasks are performed under binocular viewing conditions where both disparity and blur are operating making accommodation and vergence closed loop systems. An accommodative response recorded in this condition would be considered as a cumulative contribution of blur accommodation and vergence accommodation. By studying the similarities / differences between vergence-

accommodation and blur accommodation in the same individual (subject), it is possible to understand the role of each system in regulating the net accommodative response.

1.3 Purpose and Rationale

From a review of the earlier sections, several important features are evident. Each of these features formed the foundation for the need to perform further investigations that would improve the current understanding of the dynamic interactions between the accommodation and vergence systems. The rationale for the investigations in this thesis was based on the following outline.

1.3.1 *Paucity of investigations on the dynamics of vergence-accommodation*

Although blur driven accommodation has been investigated in detail comparatively few studies have investigated changes in accommodation due to disparity. Vergence-accommodation and its dynamic properties have been poorly studied and many of its dynamic properties remain unknown. Earlier studies have reported only a descriptive analysis of vergence-accommodation leaving many aspects of first order and second order dynamics undetermined. Main sequence analysis has gained popularity in its use for the accommodation system but no study has applied this analysis to investigate the dynamics of vergence-accommodation. So, in summary, there is a paucity of information and investigations on vergence-accommodation are necessary.

1.3.2 Influence of the dynamic differences between convergence and divergence on vergence-accommodation

Investigations of the dynamic differences between convergence and divergence have shown variable results. Recently, divergence has been shown to exhibit dynamic properties that change with initial *'starting position'* (Alvarez, Semmlow, & Pedrono, 2005). With vergence and accommodation known to interact with each other through neurological couplings it becomes obvious to question if the differences found between convergence and divergence would impact on vergence-accommodation. One study has investigated this question but it provided qualitative information only. An empirical study is needed to confirm this finding and provide a more detailed understanding.

1.3.3 Monocular blur driven accommodation vs. open-loop vergence-accommodation

Under normal viewing conditions, binocular vision is maintained necessitating both accommodation and vergence systems to act as closed loop control systems. The net accommodative response under these contributions would be an effective combination of blur accommodation and binocular vergence-accommodation. However, no information is known about the characteristic differences between these two components. Are the dynamic parameters different between vergence-accommodation and accommodation due to blur? or Do they have similar dynamic properties when both vergence-accommodation and blur accommodation are tested on the same subject? These questions still remain unanswered. Initial results from the animal models suggest that vergence-accommodation

has a greater gain and shorter phase lag but this result needs to be empirically tested and confirmed in human subjects.

1.3.4 Instrumentation limitations

One of the main reasons for the paucity of investigations that simultaneously measured response dynamics of accommodation and vergence was the lack of suitable instrumentation. Available optometers, haploscopes and eye trackers were specifically constructed to allow the measurement of response dynamics from one system only (for example accommodation). There were no commercial devices that allowed for response measures from both accommodation and vergence. Studying accommodation and vergence responses simultaneously requires the synchronization between two individual devices. Although synchronizing two separate devices (one for measuring accommodation and one for measuring vergence) appeared possible, the procedure for such a process was complicated and had a history of being accomplished on only specific types of devices (typically earlier model optometers) that allowed such versatility. In essence, if this idea were to be adopted and applied to currently available instrumentation, it would be necessary to develop a new method to successfully to synchronize two individual devices (for example the synchronization of a stereo eye tracker and an optometer so that vergence and accommodation could be measured simultaneously).

Accordingly, the objectives of this thesis were to develop the necessary instrumentation and use it to investigate the dynamic interactions between vergence and accommodation and to compare the differences between accommodation driven by blur and

accommodation driven by retinal disparity in human subjects. The following chapters detail experiments that were conducted.

2 Dynamic measures of stimulus vergence, vergence-accommodation and blur driven accommodation

2.1 Purpose

The purpose of this study was to investigate the dynamic properties of vergence-accommodation (VA) to known measures of stimulus vergence. VA dynamics were measured using a commercially available photorefractor (PowerRefractor, Multichannel systems, Germany) and the responses were compared to the dynamics of monocular blur driven accommodation.

2.2 Instrumentation

2.2.1 Stimulus vergence-accommodation

The measurement of vergence-accommodation requires blur accommodation to be open-loop while a sufficiently strong stimulus remains for vergence. Accordingly, a target was presented which provided cues to retinal disparity but not blur, while the PowerRefractor continuously recorded the accommodative response. Vergence was calculated from the stimulus demand while vergence-accommodation was measured as a change in accommodative response using a photorefractor.

2.2.2 Disparity Stimulus Generator (DSG)

The disparity stimulus generator (DSG) is a part of the commercially available Stereo eye tracker assembly (ELMAR 2020, Downsview, Ontario). The DSG acts as a stimulus

creation / projection device and is triggered by the stereo eye-tracker. The principle and application of the stereo eye tracker is discussed in **section 3.2.1**. Although the DSG is a part of the eye tracker assembly, for this study, the operation of the DSG was extended and improved to perform as an independent device without coupling it with the eye tracker.

The DSG uses a stereo-monitor assembly to create targets having retinal disparity. Fundamentally, in order to create a retinal disparity each eye has to see the target from a slightly different perspective. This is achieved easily by creating a horizontal separation between the targets **(Figure 2.1)**. If there is a horizontal separation between the targets seen by each eye, retinal disparity is created which in turn will trigger the appropriate eye movement (convergence / divergence) depending on the sign of the disparity (crossed / uncrossed). On the other hand, if there is no horizontal separation between the targets, then no disparity is created and no eye movement would be necessary. Furthermore, as the horizontal separation between the targets increases the disparity that is created also increases.
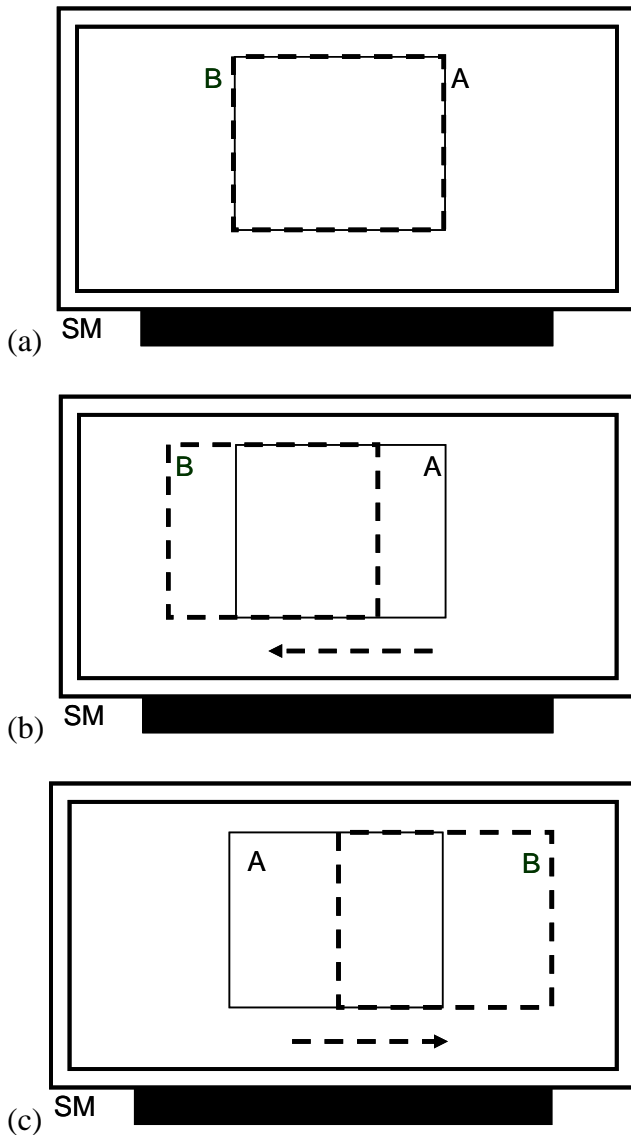
Figure 2.1 Schematic representation of the principle used by the DSG to present two targets in disparity. Target A (solid line) is seen by the left eye and target B (dashed line) is seen by the right eye. Both the targets are projected on the stereo monitor (SM). If the targets are separated horizontally a disparity is created. The direction of this separation (horizontal displacement) determines whether the disparity will be crossed or uncrossed. For example crossed disparity can be created by displacing target B horizontally to the left [indicated by the left arrow] or by displacing target A horizontally to the right [indicated by the right arrow]. The figure demonstrates three examples namely, (a) Zero disparity, (b) Crossed disparity, and (c) Un-crossed disparity. In the figure, (b) and (c) represent crossed and uncrossed disparities as an asymmetrical vergence paradigm.

The DSG consists of three devices namely a stereo-monitor, computer and liquid crystal shutter (LCS) goggles. The computer enables the presentation of the targets on the stereo monitor (Viewsonic P225fb) at a vertical refresh rate of 118Hz. The stereo monitor is

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also synchronized with the liquid crystal shutter goggles (worn by the subject), such that the images to the right and left eyes are interleaved at the same refresh rate as the monitor (118Hz).

The display on the stereo monitor is determined by a set of instructions compiled on a 'stereo file' (SDS file). The stereo file is an inherent part of the DSG and provides details about the stimulus parameters including target specifications and magnitude of disparity. The stereo file can be executed directly from the DSG or triggered from the stereo eye tracker. In this study, the stereo file was executed directly from the DSG.

2.2.2.1 Modification of the DSG and presentation of the difference of Gaussian target

Initially, the DSG allowed only an optical cross target to be presented in disparity. However, this target could not be used for testing vergence-accommodation. In order that non-accommodative targets (gratings/ blurred images) could be displayed, the software algorithm of the DSG was modified to allow complex images/gratings to be displayed on the stereo monitor. This modification was done by the manufacturer based on my specifications. The improved version of the DSG software now supports the display of targets such as gratings or any 24-bit bitmap picture. A one dimensional difference of Gaussian target (Kotulak & Schor, 1987) was created using the Psychophysics Toolbox in MATLAB R-12 (Version 6.5, MathWorks Inc, USA). The difference of Gaussian target had a peak spatial frequency of 0.2 cpd and width of the bright bar was 2.19

degrees. The target was created in MATLAB R-12 was then exported to the DSG as a 24-bit bitmap. **Appendix 2** provides details on the improved DSG interface.

2.2.3   PowerRefractor

2.2.3.1 Principle

The PowerRefractor operates on the principle of eccentric photorefraction. In this method, infrared light from eight clusters of LED (light emitting diodes) positioned around the circumference of a CCD camera lens (1m focal length) is reflected from the eye back into the camera. The pupillary light distribution, which varies with the eye's defocus, is used to estimate the accommodative response (relative change in the vertical meridian refractive error) (Bobier & Braddick, 1985;Howland, 1985). The arrangement of the extended light source and the symmetrical arrangement of the LED's reduce the effect of monochromatic aberrations of the eye (Roorda, Campbell, & Bobier, 1997). During a typical measurement, the PowerRefractor algorithm first detects the corneal Purkinje image and then outlines the pupil diameter. The brightness profile across the pupil is then calculated and the slope of this profile is converted into refractive error using a calibration equation. Photorefractive techniques have always required an initial calibration since the accuracy of the output is strongly dependent on how well the system is initially calibrated (Bobier & Braddick, 1985; Schaeffel, Wilhelm, & Zrenner, 1993; Suryakumar & Bobier, 2002). The PowerRefractor incorporates an inbuilt calibration equation which can be revised / edited to allow the input of individual calibration equations as well.

2.2.3.2 Operation

The PowerRefractor operates under five different modes namely, monocular, binocular, complete refraction, fast screening and 3D re-construction. Of these 5 modes, the monocular and binocular modes of measurement deal with dynamic measurement of accommodation at a sampling rate of 25Hz. Accommodation, pupil size, and gaze position (for the left and right eyes) are output every 0.04 seconds. The binocular mode of the PowerRefractor has been used earlier to measure the sVA/V ratio and response duration of convergence-accommodation in pre-school children (Suryakumar & Bobier, 2004). The PowerRefractor has also been used by other studies in the investigation of blur driven accommodation dynamics (Kasthurirangan, Vilupuru, & Glasser, 2003; Vilupuru, Kasthurirangan, & Glasser, 2004).

2.2.4   Blur driven Accommodation

2.2.4.1 Badal Optical System

In order to present stimuli for recording monocular blur driven accommodation a Badal optometer arrangement was designed. The targets were two high contrast (black on white) vertical lines that were back illuminated by white LED lights. The far target was placed at the focal point of the 5D Badal lens and was also conjugate with the nodal point of the eye. The second target (near) could then be placed at different distances between the Badal lens and the far target to create the appropriate accommodative demand. This accommodative demand was set to range from 1 – 2.5D in 0.5D steps. A semi-silvered mirror allowed the accommodative response to be measured simultaneously by the

PowerRefractor as the target presentations changed from far to near and vice versa. In order to identify the onset of the target and synchronize it with the PowerRefractor, I designed an input / output control box that would mark the onset of the target on the PowerRefractor interface as a 'flag' so that it was easily identified during analysis.

2.3 Methods

2.3.1 Subjects

Six subjects (26.8±3.11 yrs) were involved in the study. All subjects had a best-corrected visual acuity of at least 20/20 in each eye and normal binocular vision. The refractive error was determined by objective non-cycloplegic retinoscopy and was found to range from -0.5D to +0.5D. The study was approved and received full ethics clearance from the Office of Research Ethics at the University of Waterloo, Ontario, Canada. Informed consent for participation was obtained from all subjects prior to their enrollment in the study.

2.3.2 Experimental procedure

The experimental procedure consisted of two sessions. The first session involved the measurement of vergence-accommodation and the second session involved the measurement of blur accommodation.

2.3.2.1 Session 1 – Measurement of vergence-accommodation

During the experiment, the software program first presented the DOG target on the stereo monitor at zero disparity (baseline). Following this, the DOG target was presented as a

crossed disparity in an asymmetrical vergence paradigm thereby providing a strong stimulus to convergence (disparity ON). The crossed disparity signal was then removed (disparity OFF) and the stimulus returned back to zero disparity (baseline). The transition from baseline to disparity ON and vice versa always took place after a random time delay between 2 and 5 seconds to avoid prediction. For both the disparity ON and disparity OFF transitions, the accommodative response of the left eye was measured through the LCS goggles by the PowerRefractor. Each subject received one trial comprising of 6 different stimulus amplitudes (2, 3, 4, 5, 6 and 7 degree step stimulus demands). A practise run was first presented to each subject to ensure that they were able to initiate and maintain fusion for the six disparity amplitudes. The subjects were instructed to fixate on the stereo monitor (set at a distance of 1.7m) and keep their head stable while they watched the targets displayed on the stereo monitor. The subjects converged and fused the disparate DOG target through the LCS goggles during the disparity ON paradigm and relaxed their eyes back to baseline during the disparity OFF paradigm. During the disparity ON paradigm the subjects also reported that the DOG target appeared to emerge in front of the screen confirming fusion of the disparate images.

2.3.2.2 Session 2 – blur accommodation

The Badal optometer arrangement described earlier was used in the measurement of monocular blur accommodation. All subjects were also individually calibrated with the PowerRefractor and measurements were obtained only from the right eye. The accommodative demand was set to range from 1 – 2.5D in 0.5D steps. All subjects received one trial of each stimulus presentation which involved four different step amplitudes (1D, 1.5D, 2D and 2.5D). The individual responses to each of these stimulus

demands were analyzed separately. During a typical experiment, the near and far targets in the Badal optometer were alternately illuminated. The change from far to near defined accommodation while the change from near to far defined dis-accommodation. The specific onset time of the near / far stimulus was randomized so as to avoid prediction. This method of target presentation through the Badal lens system ensured constant retinal image size with increasing stimulus amplitudes (Bennet & Rabbetts, 1989; Atchison, Bradley, Thibos, & Smith, 1995).

2.3.2.3 PowerRefractor Calibration

Before the PowerRefractor could be used in the measurement of vergence-accommodation it was necessary to calibrate it. Since the PowerRefractor had an inbuilt reference calibration equation, it was necessary to check if the instruments calibration could be used for the measurement of vergence-accommodation in this study. Accordingly, a calibration procedure was set up that required the subject to view a high contrast accommodative target at distance with one eye (example, left eye). An infrared filter (Kodak 87B, IR filter, Rochester, NY) was placed in front of the other eye (right eye), which blocked visible light but allowed the IR light from the PowerRefractor. Ophthalmic lenses (in ±0.50-D steps up to ±4 D) were placed in front of the right eye (the eye with the filter) to induce refractive error. The resulting refractive error of the right eye through the lens and filter was measured using the PowerRefractor. This measured refractive error (Y) was then plotted as a function of the induced refractive error (X; ophthalmic lenses from 0 to 4 D). The data were fit with a linear regression and the slope of the regression was compared against a 1:1 relationship. If the PowerRefractor reliably assessed the refractive error, then we would expect no difference in the slope of the plot

compared to a 1:1 line. The same calibration procedure was also repeated on one subject with LCS goggles. The results are summarized in **Appendix 3 (section 7.2)**.

2.4 Analysis

Since the PowerRefractor only provided accommodative measures every 0.04 secs, there was a need to interpolate the data with a continuous curve. Accordingly, the accommodative measures obtained at 25 Hz from the PowerRefractor were interpolated to a continuous function using cubic polynomials (Statistics Toolbox, MATLAB (R12), Mathworks Inc. USA) (Suryakumar & Bobier, 2004). This provided an objective analysis of the response parameters. The start and end of the accommodative response were identified by determining the points where the derivatives of the polynomial solved for zero. Amplitude was defined as the absolute difference in accommodation between the start and end of the response. In addition, the cubic polynomial was differentiated and peak velocity was defined as the maximum velocity of the differentiated curve. Furthermore, the amplitude of VA response was plotted as a function of the stimulus demand and the slope of the function was defined as the stimulus VA/V ratio for each subject.

2.5 Results

2.5.1 Calibration of the PowerRefractor

When induced refractive error (X) was plotted against measured refractive error (PowerRefractor, Y), the pooled slope (for all the 6 subjects) of the linear regression fit was found to be 0.99 (R^2 value = 0.99). The measured slope was not statistically different

from a 1:1 line. This result confirmed that the reference calibration of the PowerRefractor could be used for the measurement of vergence-accommodation. Details on this calibration procedure are summarized in **Appendix 3**.

2.5.2   *Static aspects of vergence-accommodation*

The stimulus VA/V ratios and the VA amplitude range for each subject is shown in **Table 2.1.** The mean sVA/V ratio was 0.11±0.04 D/Δ (0.72±0.28 D/M.A).

Subject	sVA/V ratio (D/PD)	sVA/V ratio (D/MA)	Range of VA amplitude (Vergence demand 2 to 7 deg)
AND	0.19	1.21	0.84 to 2.45
AG	0.10	0.62	0.36 to 1.51
MI	0.06	0.39	0.49 to 1.30
RJ	0.08	0.55	0.44 to 1.30
SU	0.14	0.82	0.82 to 2.39
MRK	0.12	0.78	0.71 to 2.07
MEAN±SD	**0.11±0.04**	**0.72±0.28**	**0.61 to 1.84**

Table 2.1 Stimulus VA/V ratios and the range of VA amplitudes for each subject.
VA/V ratio was calculated as the slope of the linear regression between stimulus vergence demand and VA response.

2.5.3 *Dynamics of vergence-accommodation*

A typical response of vergence-accommodation during the disparity ON and OFF paradigm is shown in **Figure 2.2**. The figure also illustrates the cubic polynomial curve fitting for the same accommodative responses. The VA responses fitted reasonably well with a cubic polynomial having an R^2 value of at least 0.83.
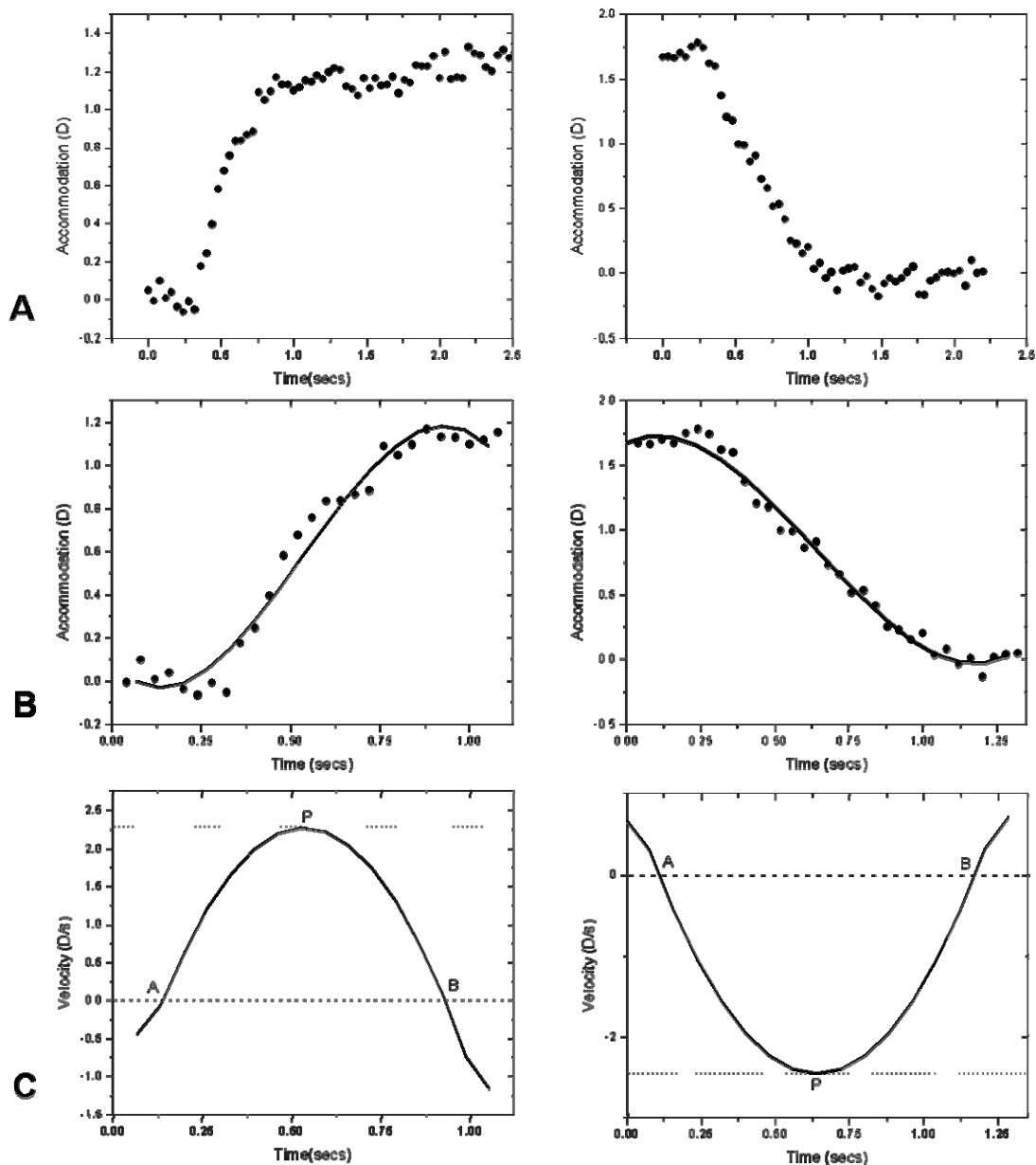
Figure 2.2 Step responses of vergence-accommodation to retinal disparity.
A. Typical result of disparity driven accommodation dynamics showing the change in accommodation for two specific stimulus transitions (disparity on and disparity off). When the disparity stimulus is on, after a short latency period, there is an increase in accommodative response because of convergence. When the disparity stimulus is off, the accommodative response is relaxed and quickly returns to its initial baseline value. B. Illustration of the cubic polynomial curve fitting technique. The solid line shows the cubic polynomial fit to the data. C. Differentiated cubic polynomial curve. Points A and B represent the start and end of the accommodative response. These points have been identified after differentiating the cubic polynomial and finding the points where the slope = 0 (dashed line, [---]). peak velocity (P) is defined as the maximum velocity in the differentiated curve (dotted line, […]).

2.5.3.1 Main sequence of vergence-accommodation

Individual linear regression slope values for the plot of peak velocity as a function of response amplitude is shown in **Table 2.2** for each subject. The individual slope values ranged form 1.07 to 1.46 for disparity ON and 1.43 to 2.10 for Disparity OFF.

	Disparity ON			Disparity OFF		
Subject	Slope	Intercept	R^2	Slope	Intercept	R^2
AND	1.26	0.45	0.91	1.61	-0.18	0.86
AG	1.46	1.14	0.47	1.58	-0.12	0.95
MI	1.07	1.71	0.71	1.69	-0.12	0.70
RJ	1.47	1.12	0.58	2.10	-0.18	0.82
SU	1.23	0.38	0.65	1.43	-0.17	0.94
MRK	1.40	0.60	0.85	1.81	-0.34	0.88
MEAN±SD	**1.32±0.16**	**0.90±0.51**	**0.69±0.16**	**1.70±0.23**	**-0.18±0.08**	**0.85±0.09**

Table 2.2 Individual values for the slope, intercept and R^2 values of the amplitude vs. peak velocity function for VA during disparity ON and disparity OFF.

The amplitude vs. peak velocity plot (pooled data from all subjects) during disparity ON and disparity OFF paradigms are shown in **Figure 2.3** Linear regression analysis of the pooled data from **Figure 2.3** showed a statistically significant linear relationship for both disparity ON (peak velocity of accommodation = 0.812 * amplitude + 1.564, R^2 = 0.452, p<0.0001) and disparity OFF (peak velocity of accommodation = 1.699* amplitude – 0.234, R^2 = 0.86, p <0.0001) paradigms. In order to test if the slope of the main sequence

was different between disparity ON and disparity OFF paradigms, the two linear regressions were compared using the F test (Zar, 1984). The results showed that the differences between the slopes were statistically significant ($F_{(1,67)} = 18.01$, p<0.0001).

The amplitudes were also divided into four different bins (0.5-1, 1-1.5, 1.5-2 and 2-2.5D) and the peak velocity across each amplitude bin was compared between disparity ON and OFF. Comparisons were done using two-way ANOVA with Bonferroni post-tests. The statistical tests were performed using GraphPad Prism version 4.00 for Windows, GraphPad Software, San Diego California USA. The results showed that overall, the peak velocity during disparity ON was significantly lower than peak velocity during disparity OFF (two-way ANOVA, $F_{(1,40)} = 11.42$, p<0.001) and the difference in the peak velocity between disparity ON and disparity OFF were not consistent across the amplitude bins showing interaction effects ($F_{(3,40)}=3.042$, p=0.039). The post-test results show that the peak velocity of VA (disparity ON) and blur accommodation were similar across all amplitude bins with the exception of 0.5 – 1D **(Table 2.3)**.
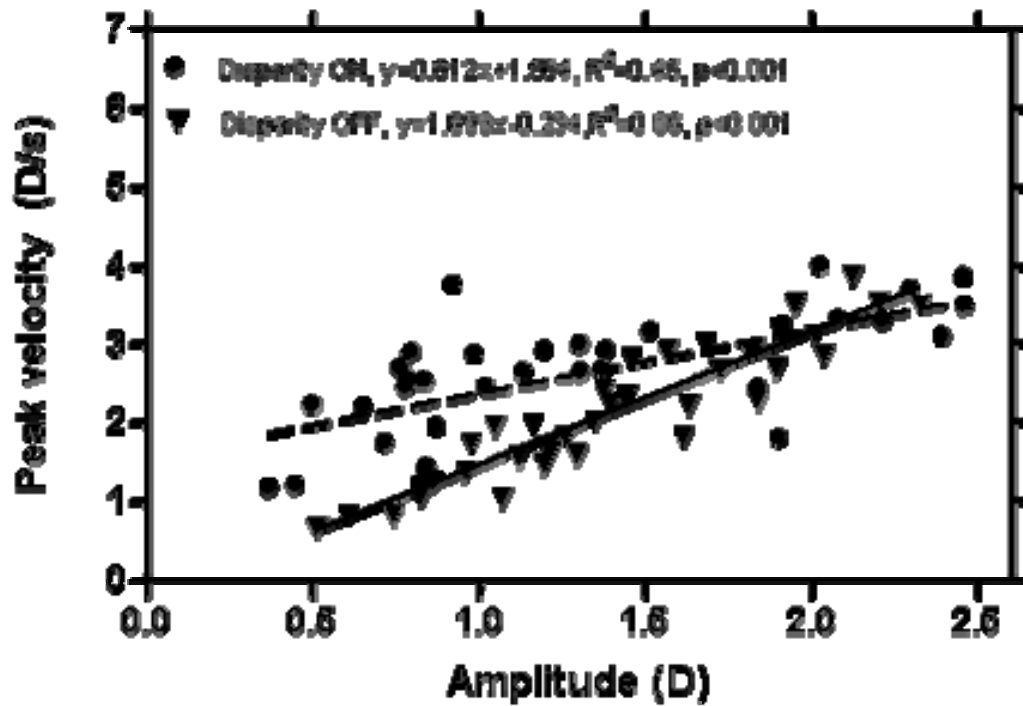
Figure 2.3 Amplitude vs. peak velocity plot for VA during disparity ON and disparity OFF.
Graph shows the results from all subjects. Both disparity ON (dashed line) and disparity OFF (solid line) linear regressions show a statistically significant linear relationship. The slopes of the linear regression functions were statistically different.

Amplitude (D)	Disparity ON (D/s)	Disparity OFF (D/s)	Difference	95% CI of diff.	t	P value
0.5 - 1	2.2	1.11	-1.09	-1.82 to -0.36	3.9	P<0.01
1 - 1.5	2.56	1.93	-0.63	-1.36 to 0.09	2.26	P > 0.05
1.5 - 2	2.95	2.81	-0.13	-0.86 to 0.59	0.47	P > 0.05
2 - 2.5	3.48	3.44	-0.04	-0.77 to 0.69	0.14	P > 0.05

Table 2.3 Comparison of peak velocity between disparity ON and disparity OFF paradigms for different amplitude bins.
The data from all the subjects were pooled and then separated into different amplitude bins. The peak velocities remained statistically non-significant across all the bins except for 0.5 – 1 D where the peak velocity of vergence-accommodation during disparity ON was significantly greater than velocity during disparity OFF.

2.5.4 Dynamics of blur driven accommodation

2.5.4.1 Main sequence

The amplitude vs. peak velocity plots for blur driven accommodation and dis-accommodation are shown in **Figure 2.4**. Individual values of the main sequence parameters (slope, intercept, R^2 value) for the six subjects are shown in **Table 2.4.** For all subjects, accommodation and dis-accommodation showed a statistically significant linear regression as a function of response amplitude (Accommodation peak velocity = 1.593 * amplitude - 0.008, $R^2 = 0.84$, p<0.001; Dis-accommodation peak velocity = 1.646 * amplitude - 0.036, $R^2 = 0.77$, p<0.001). When the slope of the two regression lines were compared using the F test (Zar, 1984), it was observed that the difference in the slope (between accommodation and dis-accommodation) was not statistically significant (Slope comparison, $F_{(1,44)} = 0.044$, p = 0.83; Intercept comparison, $F_{(1,45)} = 0.154$, p=0.69).

The accommodative response amplitudes were separated into different amplitude bins (0.5 – 1D, 1 – 1.5D, 1.5 – 2D, 2 – 2.5D) and the peak velocity of accommodation and dis-accommodation were compared. The results of the two-way ANOVA showed that peak velocity during accommodation and dis-accommodation were similar ($F_{(1,40)}$=0.141, p=0.709) and the differences in the peak velocity between accommodation and dis-accommodation were consistent for each amplitude bin ($F_{(3,40)}$=1.615, p=0.201). Bonferroni post-tests results showed that the peak velocity of accommodation and dis-accommodation were also similar across all the amplitude bins (**Table 2.5**).
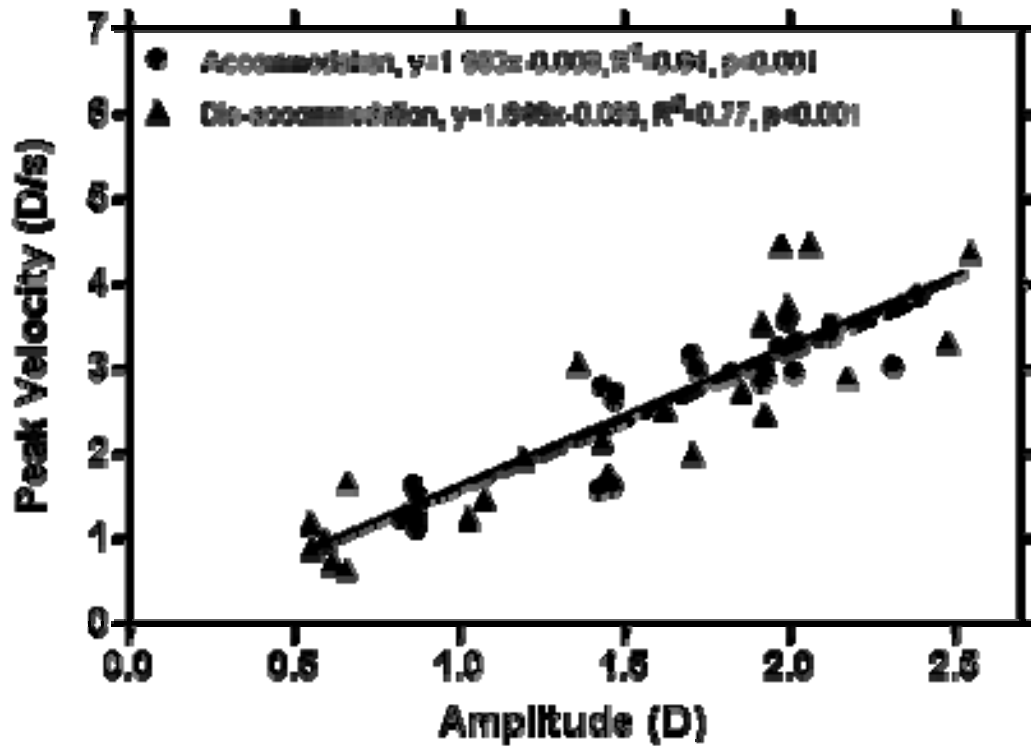
Figure 2.4 Amplitude/peak velocity plots for blur-driven accommodation and dis-accommodation. The slope of linear regression for dis-accommodation (solid line) was marginally higher when compared to accommodation (dashed line). However, this difference did not reach statistical significance.

Subject	Accommodation			Dis-accommodation		
	Slope	Intercept	R^2	Slope	Intercept	R^2
AND	1.68	-0.28	0.76	1.54	0.27	0.94
AG	1.45	0.49	0.95	1.63	0.15	0.81
MI	1.75	-0.24	0.99	1.29	0.06	0.91
RJ	1.83	-0.68	0.92	1.82	-0.71	0.94
SU	1.12	0.74	0.84	2.63	-0.76	0.99
MRK	1.76	-0.12	0.95	1.26	0.21	0.95
MEAN±SD	**1.60±0.27**	**-0.01±0.52**	**0.90±0.08**	**1.69±0.50**	**-0.13±0.47**	**0.92±0.06**

Table 2.4 Individual main sequence parameters (slope, intercept, R^2 values) of accommodation and dis-accommodation for the six subjects.

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Amplitude	Accommodation (D/s)	Dis-accommodation (D/s)	Difference	95% CI of diff.	t	P value
0.5 - 1	1.34	1.02	-0.32	-1.13 to 0.50	1.01	P > 0.05
1 - 1.5	2.26	1.90	-0.36	-1.18 to 0.46	1.15	P > 0.05
1.5 - 2	3.12	3.06	-0.06	-0.88 to 0.75	0.21	P > 0.05
2 - 2.5	3.34	3.85	0.50	-0.31 to 1.32	1.61	P > 0.05

Table 2.5 Comparison of the peak velocities of accommodation and dis-accommodation across different amplitude bins.
The peak velocity of accommodation and dis-accommodation was similar across all amplitudes.

2.5.5 *Comparison of vergence-accommodation and blur accommodation*

Figure 2.5 and 2.6 show the amplitude vs. peak velocity relationships for VA (disparity ON) vs. blur accommodation and VA (disparity OFF) vs. blur dis-accommodation respectively. Since blur accommodation and vergence-accommodation were both defined in dioptre units, the response amplitudes were separated into different bins and the peak velocities were compared between the two systems using a two-way ANOVA with Bonferroni post-tests. The results are summarized in **Table 2.6 and 2.7**.

The results of this study clearly showed that linear regression functions of the amplitude vs peak velocity relationship between VA (disparity ON) and blur driven accommodation were significantly different ($F_{(1,56)}$=10.45 p=0.002) **(Figure 2.5)**. Overall across all amplitude bins, the peak velocity of VA during disparity ON was significantly different

from peak velocity of accommodation ($F_{(1,40)}$=4.679, p<0.036). Bonferroni post-tests results showed that the difference in the peak velocity between VA (disparity ON) and blur accommodation at 0.5 – 1D amplitude was significantly different **(Table 2.6)**. At all other amplitude levels, the differences in the peak velocity between VA and blur accommodation did not reach statistical significance.

On the other hand, when VA responses during disparity OFF and blur dis-accommodation were compared our results showed that the peak velocity of VA during disparity OFF was similar to peak velocity of dis-accommodation. The linear regression functions describing the relationship between amplitude vs peak velocity were also found to have similar slope and intercept values between VA (disparity OFF) and blur dis-accommodation ($F_{(1,55)}$=0.058, p=0.80) **(Figure 2.6)**. Bonferroni post-test results also showed that peak velocity of VA (disparity OFF) and blur dis-accommodation were similar for all amplitude bins ($F_{(1,40)}$=0.656, p=0.422) (**Table 2.7**).
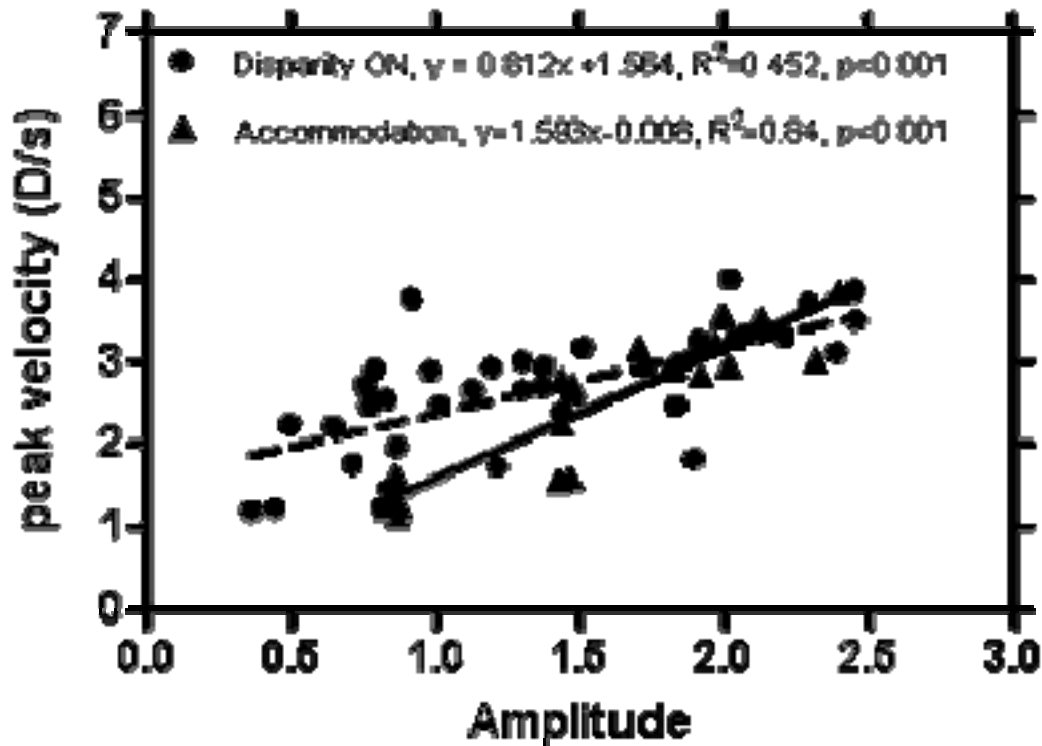
Figure 2.5 Amplitude vs. peak velocity relationship comparison for VA (disparity ON) and blur accommodation.
The slope of the linear regression function was significantly different between VA (disparity ON) (dashed line) and accommodation (solid line).

Amplitude	Disparity ON (D/s)	Accommodation (D/s)	Difference	95% CI of diff.	t	P value
0.5 - 1	2.20	1.33	-0.86	-1.54 to -0.18	3.33	P<0.01
1 - 1.5	2.56	2.26	-0.30	-0.98 to 0.38	1.16	P > 0.05
1.5 - 2	2.95	3.12	0.18	-0.50 to 0.86	0.68	P > 0.05
2 - 2.5	3.48	3.34	-0.13	-0.81 to 0.54	0.52	P > 0.05

Table 2.6 Comparison of peak velocity between VA (disparity ON) and blur accommodation across four different amplitude bins.
two-way ANOVA (with Bonferroni post-tests) shows a statistically significant difference only at 0.5 – 1D. The peak velocity of VA (disparity ON) and blur accommodation were similar at all other amplitude bins.

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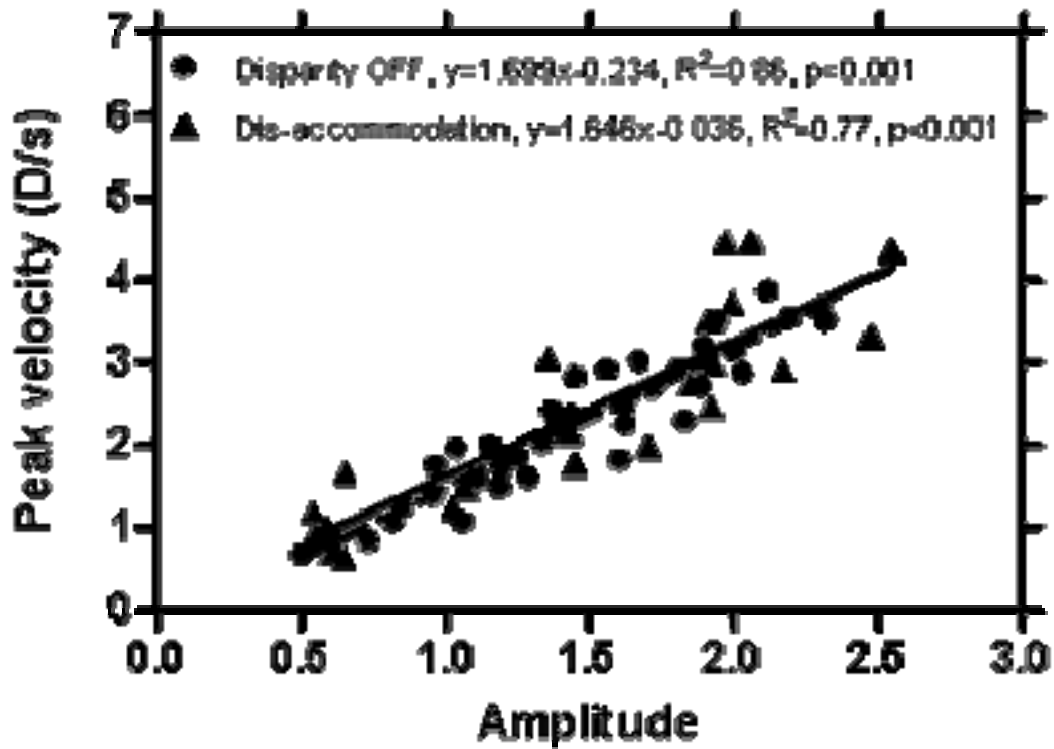
Figure 2.6 Amplitude vs. peak velocity plot for VA (disparity OFF) and blur dis-accommodation.
VA (dashed line) blur accommodation (solid line) show considerable overlap at across the entire amplitude suggesting similar dynamic properties.

Amplitude	Disparity OFF (D/s)	Dis-accommodation (D/s)	Difference	95% CI of diff.	t	P value
0.5 - 1	1.11	1.02	-0.09	-0.95 to 0.77	0.28	P > 0.05
1 - 1.5	1.93	1.90	-0.03	-0.89 to 0.83	0.09	P > 0.05
1.5 - 2	2.81	3.06	0.24	-0.62 to 1.10	0.74	P > 0.05
2 - 2.5	3.44	3.85	0.41	-0.45 to 1.27	1.24	P > 0.05

Table 2.7 Comparison of peak velocity between VA (disparity OFF) and blur dis-accommodation across four different amplitude bins.
two-way ANOVA (with Bonferroni post-tests) shows a statistically non-significant difference across all amplitude bins.

2.6 Discussion

2.6.1 *General conclusions on the dynamics of vergence-accommodation*

The main result of this study is related to the amplitude vs peak velocity relationships (main sequence). Although the main sequence typically outlines the first order dynamic properties over a wide range of response amplitudes as a non-linear exponential function (Bahil, Clark, & Stark, 1975), only a small range of amplitude was studied in this investigation and hence the results could be fit with a linear function. The disparity amplitudes used in the current study were limited to a maximum of 7 degrees and the maximum amplitude of vergence-accommodation measured was approx 2.5D (**Table 2.1**). For this small range of VA amplitudes, linear regression equations could be used to describe the amplitude vs. peak velocity relationships. The results have shown that the dynamics of convergence accommodation are amplitude dependent. peak velocity of VA increased linearly with response magnitude during disparity ON and disparity OFF paradigms. However, the rate of change (slope of the linear regression function) of peak velocity as a function of response magnitude was lower during disparity ON compared to disparity OFF. If this was a true effect, then convergence and divergence responses might also be expected to show differences in their dynamic properties. However, this study did not measure disparity vergence response; it was only assumed from the stimulus measure. Therefore it is not possible to conclude whether or not the difference in the peak velocity of VA was due to fundamental differences in the dynamic properties of convergence and divergence. Measurements of vergence dynamics coupled with vergence-accommodation would be necessary to confirm this finding.

The current study results can be compared to the results of Krishnan et al. (1977). For the same response amplitude (1.8D), Krishnan et al. (1977) suggested that divergence driven decrease in accommodation was much slower than convergence driven increase in accommodation both in terms of latency and speed of response. However, the velocities of these responses were not measured and the suggestion made by the authors was solely based on qualitative information obtained from visual inspection of the averaged accommodation traces between the two conditions. For this study, 1.8D of vergence-accommodation would be in the higher range of VA amplitude. From **Figure 2.3**, vergence-accommodation amplitude of 1.8D would represent a point very close to the intersection of the two linear regressions. At this point, the peak velocity during disparity OFF was only marginally lower than the peak velocity during disparity ON. The two-way ANOVA comparisons for this amplitude bin (1.5 – 2 D) showed that the difference in the peak velocity between disparity ON and disparity OFF was not statistically significant **(Table 2.3)**.

It is also important to note two main crucial differences between the two studies in terms of stimulus presentation. Krishnan et al. (1977) provided both crossed and uncrossed disparities from the same baseline position to directly stimulate reflex convergence and divergence respectively. However, in our study, we used a disparity ON / OFF paradigm that presented only crossed disparities as step demands from baseline for a brief time interval, and then the disparity stimulus was removed so that the eyes could return back to their initial position (zero disparity). Furthermore, Krishnan et al. (1977) provided a single step demand of crossed and uncrossed disparity that always changed from a fixed

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baseline (zero level) to a fixed near position (amplitude = 4.5 deg). In this study, the stimulus demand for disparity ON always changed from the *same* baseline to *different* near positions and the stimulus demand for disparity OFF changed from *different* near positions to the *same* baseline. Hence, there is a possibility that either the initial starting position or the amplitude of the stimulus (or both) could have influenced the response dynamics during disparity OFF making them faster as the initial starting position shifted proximally. This would also explain why the results of our study showed VA responses during the disparity OFF paradigm to be faster as amplitudes increased. It is also interesting to note that similar effects of initial start position and amplitude have recently been shown to influence the dynamic responses of blur driven accommodation, dis-accommodation (Kasthurirangan & Glasser, 2003) and disparity driven divergence (Alvarez, Semmlow, & Pedrono, 2004).

2.6.2 *Main sequence of monocular blur-driven accommodation*

A comparative summary of the current study and previous study results on the main sequence relationship for accommodation and dis-accommodation is presented in **Tables 2.8 and 2.9** respectively.

Investigation	Subjects (N)	Age	Amplitudes tested	Slope of main sequence
Ciuffreda and Kruger (1986)	5	22 - 38	0.1 – 3D	Linear
Kasthurirangan et al. (2003)	8	20 – 30	0 – 8D	No clear relationship/ high variability
Mordi and Ciuffreda (2004)	5	21 – 30	0.1 – 2D	0.83
Bharadwaj and Schor (2004)	6	23 – 35	0 – 4D	0.72 – 1.76
Current study	6	22 – 30	0 – 2.5D	1.59

Table 2.8 Summary of study results on the main sequence of blur driven accommodation.
The slope of the linear portion of the main sequence relationship is indicated in the last column. From the table it can be observed that the slope values are quite variable when compared between the investigations.

Investigation	Sample	Age	Amplitudes tested	Slope of main sequence
Kasthurirangan et al. (2003)	8	20 – 30	0 – 8D	4.18
Our study	6	22 – 30	0 – 2.5D	1.65

Table 2.9 Summary of study results on the slope of the amplitude vs. peak velocity relationships during blur dis-accommodation.
Only one study has reported on dis-accommodation dynamics for a wide range of amplitudes.

From **Table 2.8** it can be observed that, when peak velocities were studied over a wide range of response amplitudes there was significant variability and no clear relationship (Kasthurirangan, Vilupuru, & Glasser, 2003). On the other hand, when response

amplitudes were limited to a smaller range, a linear regression function could be fit to describe the amplitude vs peak velocity relationship (Mordi & Ciuffreda, 2004; Bharadwaj & Schor, 2004). However the slope of this regression appears to be different from the results of Mordi & Ciuffreda (2004). Both studies recorded accommodation responses in young adults over a similar range of stimulus amplitudes but the main sequence slope for accommodation in the current study was higher than that of Mordi and Ciuffreda (2004). This difference could be attributed to a number of factors including, differences in instrumentation, analysis of the accommodative responses, and inter-individual variability of dynamic accommodation. The current study recorded dynamic accommodation using a PowerRefractor at 25Hz while Mordi and Ciuffreda (2004) used a high speed Canon R1 autorefractor (100 Hz). Also, the analysis of the accommodation responses to derive peak velocity was different between the two investigations. Furthermore, accommodation responses for the same stimulus demand have been known to exhibit significant inter-individual variability (Schaeffel, Wilhelm, & Zrenner, 1993) and this could have resulted in variations in the response dynamics between the two investigations. Individual variations in the main sequence slopes have also been shown in a recent study by Bharadwaj and Schor (2004) where the linear portion of the main sequence was found to range from 0.72 – 1.76. This range includes the slope measures found in the current study as well as that found by Mordi & Ciufreda (2004).

Compared to accommodation, ocular dis-accommodation has been poorly studied. So far only one study has reported on its main sequence (Kasthurirangan, Vilupuru, & Glasser, 2003). The results of Kasthurirangan et al. (2003) demonstrate a linear change in dis-

accommodative peak velocity for the entire range of response amplitudes (0 – 8D). The slope of this regression is significantly greater when compared to the slope measure of dis-accommodation obtained in this study (**Table 2.9**). Possible reason for this difference is the smaller range of amplitudes in the current investigation. The biomechanical properties of the crystalline lens suggest that dis-accommodation tends to become progressively faster as higher amplitudes are reached (Kasthurirangan, Vilupuru, & Glasser, 2003). Since the current study limited stimulus amplitudes to modest demands, it is possible that if higher amplitudes were included the main sequence relationship would become steeper reflecting a greater rate of change of peak velocity with response magnitude.

2.6.3 *Vergence-accommodation vs. blur accommodation*

The results from this study have also compared the first order dynamics of vergence-accommodation and blur accommodation. The results show that, overall, the rate of change of peak velocity with response magnitude was significantly greater for blur accommodation compared to vergence-accommodation (disparity ON). Bonferroi post-tests on different amplitude bins have shown that the peak velocities of VA and blur accommodation are different at lower amplitudes. Whether this difference is a true measure or variability needs to be further investigated. It should also be recognized that in order to effectively compare the two systems and outline differences/similarities, several response parameters need to be taken into account. This study only compared the peak velocity between vergence-accommodation and blur accommodation and hence no information is known about other temporal parameters. A more detailed and complete

analysis of all temporal parameters is required to confirm if blur accommodation and vergence-accommodation have different or similar dynamic properties.

2.6.4   Limitations of the study

2.6.4.1 Cubic polynomial interpolation

Although the current study results have provided valuable information on the first order dynamics of vergence-accommodation, there are also a few important limitations that need to be identified. The current study used the PowerRefractor to measure vergence-accommodation. This device sampled at 25Hz and hence an interpolation function was necessary to analyze the accommodative response and calculate the temporal parameters. However, the interpolation technique suffered from an under-estimation of vergence-accommodation peak velocities at higher amplitudes. This drawback of the cubic polynomial interpolation was specifically related to the higher amplitude vergence-accommodation responses obtained during the disparity ON paradigm. For the VA responses during disparity ON, the peak velocities appeared to be under-estimated. A qualitative visual inspection of the cubic polynomial fit from **Figure 2.3** shows that the polynomial curve does not match with the position response of vergence-accommodation. The initial rising portion of the polynomial curve after response onset tends to be relatively flat when compared to the actual position response. Since velocity was directly estimated from the differentiation of the polynomial curve, it is possible that the peak velocity for the higher response amplitudes could have been under-estimated. This could also be the reason for the linear regression function to be relatively flat for the disparity ON paradigm compared to disparity OFF. On the other hand, for the responses of

vergence-accommodation during disparity OFF, the polynomial curve fit the data better and response parameters were more accurately calculated. The polynomial curve matched up with the position responses of VA during disparity OFF so the estimation of the peak velocity was accurate.

2.6.4.2 Measurement of vergence response

Another issue that was a limitation in this study relates to the measurement of vergence position. The PowerRefractor did not allow for any external devices (example eye trackers) to operate simultaneously in view of hardware conflicts. Vergence position had to be assumed from the theoretical stimulus demand. Although the study results found differences in the velocity of vergence-accommodation during disparity ON (convergence) and disparity OFF (divergence) it is not known if vergence dynamics also showed a similar effect. Hence there arises a need for the simultaneous measurement of accommodation and vergence.

2.6.4.3 Sampling rate of the PowerRefractor

Interpolation techniques such as cubic polynomials were necessary because of the low sampling rate of the PowerRefractor. Response parameters could not be directly calculated from the raw accommodative response due to noise. The sampling rate of the PowerRefractor is fixed and cannot be modified due to hardware/camera limitations of the device. Although this sampling rate is higher than the nyquist limit for accommodation (Pugh, Eadie, Winn, & Heron, 1987) and hence sufficient to identify the fundamental dynamic characteristics of the response, it is definitely insufficient when higher order dynamic properties need to be investigated. Specifically, the acceleration

signals which are known to occur early in the response may be missed if the responses were measured at a lower sampling rate. Also, a higher sampling rate would avoid an interpolation technique that tends to *linearize* the data with a continuous curve. The PowerRefractor limitations in this study did not allow the estimation of second order or equivalent second order properties in the response specifically because of the lower sampling rate. Therefore, there is a need for a faster photorefractor which would allow a better resolution of accommodative position. With higher sampling there is a greater resolution of the response position which would allow a more accurate estimation of lower order and higher order dynamics.

This can be better understood by considering the following example. **Figures 2.7, 2.8 and 2.9** show the accommodative response position, velocity and acceleration traces respectively of the same data set at two different sampling rates namely 25 and 75 Hz. Velocity and acceleration were estimated using a direct differentiation technique which involves averaging the slopes of two adjacent data points. The position traces were first differentiated to obtain velocity and further differentiated to obtain acceleration. The velocity and acceleration traces were then subsequently smoothed using an FFT smoothing function. Although the original measures were obtained at 75 Hz, to illustrate the effect of sampling, the same data set was re-sampled to 25 Hz.
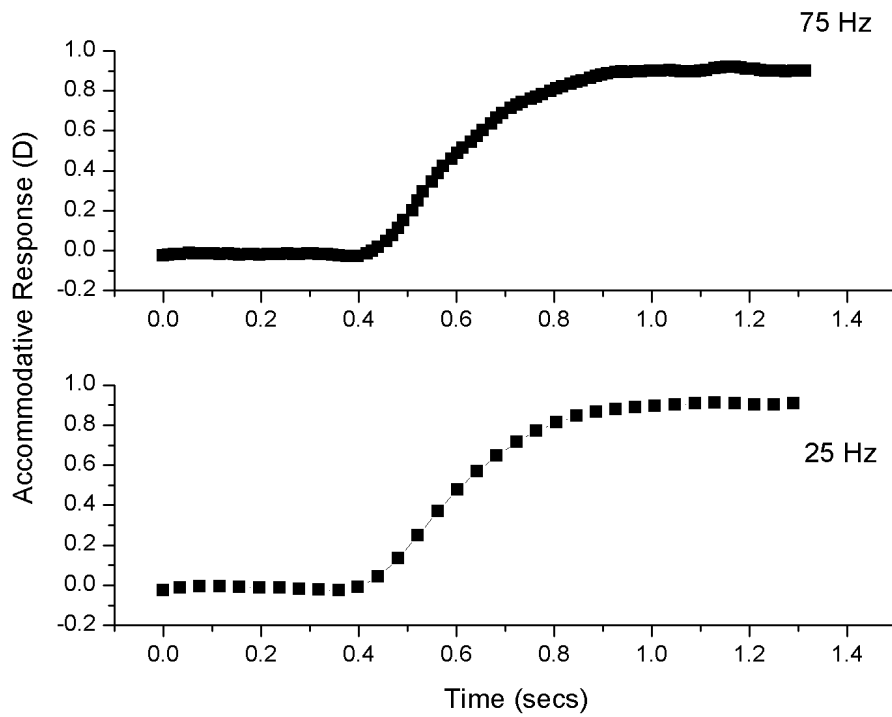
Figure 2.7 Accommodative response position at two different sampling rates (25 and 75 Hz).
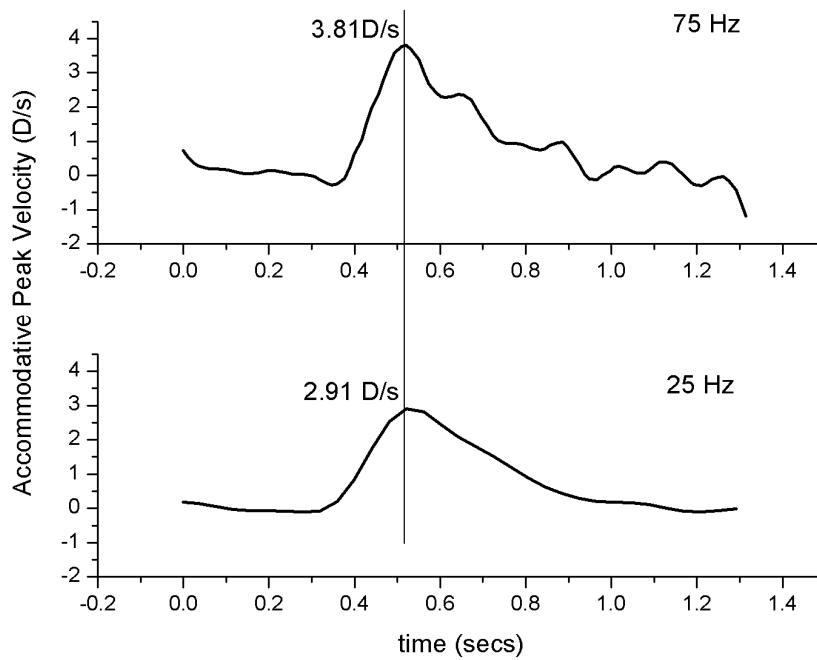
Figure 2.8 Velocity profiles of the accommodative response position for the two samples.
The magnitude of the peak velocity is indicated for each plot. It is apparent that the peak velocity is lower when sampled at 25 Hz compared to 75 Hz.
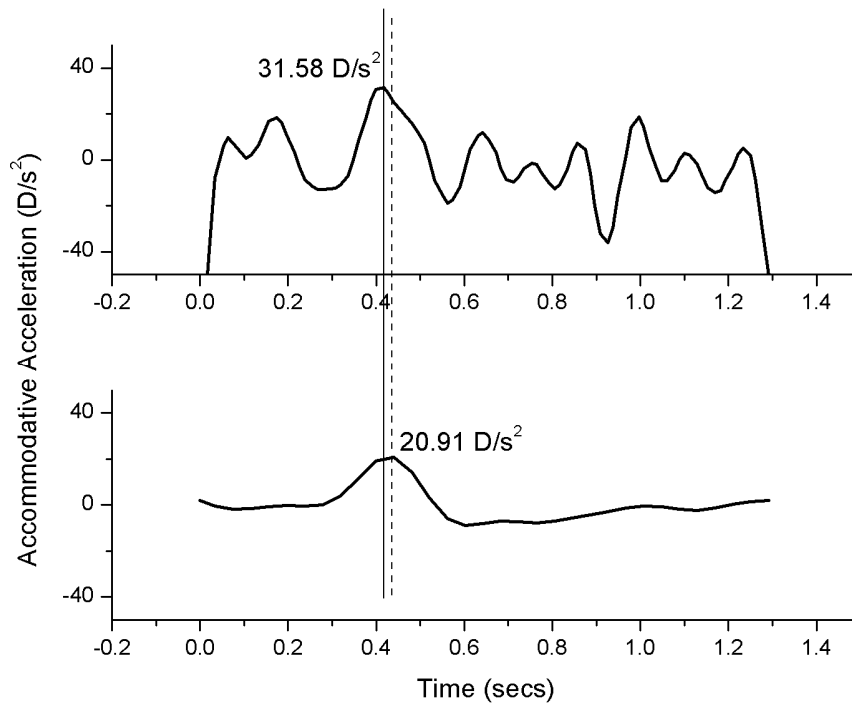
Figure 2.9 Acceleration profiles of the two samples (25 Hz and 75 Hz).
Note that the magnitude of peak acceleration is lower for 25 Hz compared to 75Hz sampling. Also, the onset of peak acceleration is shifted in time for the 25 Hz sampling.

Figure 2.8 and 2.9 show that the magnitudes of peak velocity and peak acceleration are under estimated when responses are sampled at a lower frequency. With the 75 Hz sampling, all the frequencies in the signal are preserved. However, when sampling decreases to 25Hz, higher order frequencies are filtered and this results in a lower velocity estimate. The actual true value of the peak velocity is reliably estimated at 75 Hz. A similar analogy applies for acceleration as well. At higher sampling rates (75Hz), higher order differentiation causes fluctuations in the acceleration trace (**Figure 2.9** top). This is mainly because of the amplification of the higher frequency signals present in the response. On the other hand, at lower sampling rates (25Hz), the velocity responses are

already smoothed (due to the loss of higher frequencies in the signal) and hence further differentiation does not cause fluctuations in the trace (**Figure 2.9** bottom).

In summary, there is a need for a new high speed photorefractor that can measure accommodative response continuously allowing for an accurate assessment of velocity and acceleration. The following study describes the development of a new high speed photorefractor and its synchronization with an eye tracker. These instrumentation developments allowed for simultaneous measures of disparity vergence and vergence-accommodation. Furthermore, they also allowed for a comprehensive study of the dynamic properties of the two ocular motor systems.

3 Dynamic measures of response vergence and high speed measures of accommodation

3.1 Purpose

The goal of this study was to compare the response dynamics of three ocular motor systems namely blur driven accommodation, disparity vergence and the vergence-accommodation cross-link. A new high speed photorefractor was designed and synchronized with a stereo eye tracker to investigate the first and second order dynamics of vergence-accommodation, to compare the dynamic response parameters of VA during convergence and divergence and to identify similarities in the dynamic properties of VA with comparable measures of accommodation driven by blur.

3.2 Instrumentation

3.2.1 Stereo eye tracker

The stereo eye-tracker system was an ELMAR 2020 eye tracker incorporated with a liquid crystal shutter goggle assembly that enables stereoscopic viewing (Elmar Inc, Downsview, Ontario) **(Figure 3.1A)**. It is a video based head mounted device that records right and left eye position. The system calculates eye rotation based on the measurement of the relative distance between the pupil center and the corneal Purkinje images.

The stereo eye tracker consists of an illumination system, a liquid crystal shutter goggle assembly, and a tracking system with two CCD cameras that capture the images of the right and left eyes. All of these systems are mounted on an adjustable light-weight head-set worn by the subject. The illumination system is powered by four infrared light emitting diodes (IR LED's) situated behind liquid crystal shutter goggles. The light from the LED's strikes the eye after reflecting from a hot mirror. The reflected light from the eye is then captured by the CCD cameras which are located on the head set **(Figure3.1B)**. A computer algorithm locates the pupil center and calculates the relative distance between the pupil center and the corneal Purkinje image **(Figure 3.1C)**. This information is then used in determining the right and left eye position. The system operates at a sampling rate of 120 Hz and records both horizontal and vertical eye movements binocularly with a resolution of $\pm$ 0.1 deg for a linear range of at least $\pm$ 30 deg in the horizontal, and at least $\pm$ 25 deg in the vertical meridian. Eye position recorded by this eye tracker has been shown to compare well with the results from a magnetic search coil technique (DiScenna, Das, Zivotofsky, Seidman, & Leigh, 1995). The stereo eye-tracker assembly included the eye tracker and the disparity stimulus generator (DSG). The DSG explained earlier in section 2.2.2 was triggered by the eye tracker.
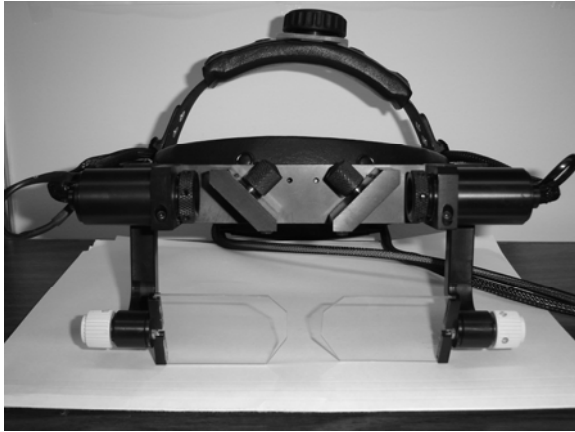
A.
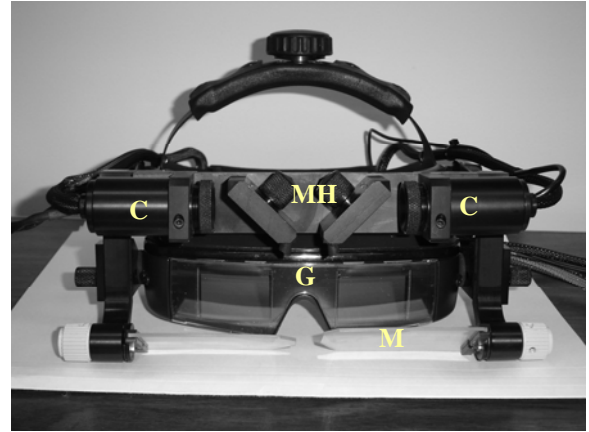
B.
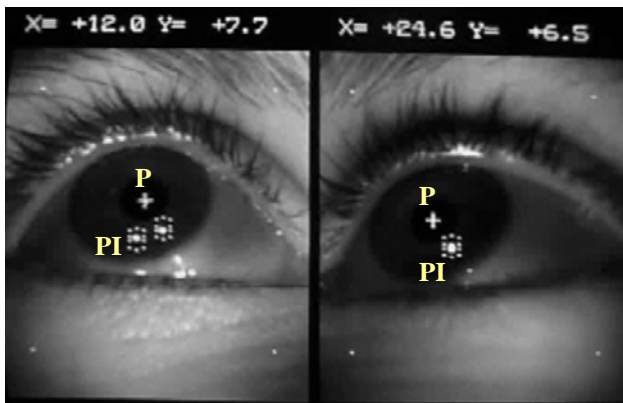
C.

Figure 3.1 ELMAR 2020 Eye tracker in the regular mode and stereo mode.
(3.1B) The stereo eye tracker (B) incorporated a LCD shutter goggle (G) with infrared LED's (not shown in the figure) positioned directly behind the goggles. The hot mirror (M) reflected the light from the LED's to the eyes; captured the reflected light coming back, and relayed it to the CCD camera (C) via the mirrors on the headset (MH). **(3.1C)** The inbuilt computer algorithm detected the pupil center (P) and the two corneal Purkinje images (PI) for each eye. Eye position was calculated by measuring the relative distance between the pupil center and the corneal Purkinje images

3.2.1.1 Integration of the Stereo eye-tracker and Disparity Stimulus Generator

The DSG and the stereo eye-tracker are run by separate computers that were synchronized (via the parallel port). The DSG controls the type of stimulus that is presented on the stereo monitor (example. grating ,bitmap) and the eye tracker controls the onset and duration of this stimulus on the DSG (**Figure 2.2**).

The eye tracker allowed for the creation of a stimulus file (*.SDF) which contained information about when the target should be displayed on the stereo monitor (onset of the stereo file) and how long the display should persist (duration) before the next instruction on the DSG could be executed. The onset of the target was coded as a spatial position such that a change in the position was interpreted as a need to change the target displayed in the stereo monitor. The examiner assigned the value for the spatial position and the duration before the start of the experiment and this information was stored in the SDF file.

During a typical experiment, when its time for the stimulus to change, the spatial position coded in the SDF file changes and this information is relayed to the computer controlling the DSG. The DSG then executes the first instruction in the stereo (SDS) file. If several spatial positions are coded in the SDF file then this process gets repeated until all the spatial positions are accounted. The cascade of these events is summarized as a flowchart in **Figure 3.2**.

```
┌─────────────────────────┐
│ Stimulus file (SDF) created │
│  in the stereo Eye tracker  │
└─────────────────────────┘
            │ (e.g. stimulus.sdf)
            ▼
┌─────────────────────────┐         (e.g. 171.sds)      ┌─────────────────────────┐
│ Input parameters (*.SDF, *.SDS) in │ ◀ - - - - - - - │ Stereo file (SDS) created │
│     Eye tracker interface      │                     │       in the DSG        │
└─────────────────────────┘                             └─────────────────────────┘
            │
            ▼
      ( Start of experiment )
            │
            ▼
      ◇ Change in SDF value? ◇ ── yes ──▶ ┌─────────────────────┐
                                          │   SDS filename sent   │ ◀──┐
            │ no                          │ to DSG via parallel port │    │
            │                             └─────────────────────┘    │
            │                                       │                 │
            │                                       ▼                 │
            │                             ┌─────────────────────┐    │
            │                             │  DSG executes the    │    │
            │                             │     stereo file      │    │
            │                             └─────────────────────┘    │
            │                                       │                 │
            │                                       ▼                 │
            │                             ┌─────────────────────┐    │
            │                             │ Target changes in the │    │
            │                             │    stereo-monitor    │    │
            │                             └─────────────────────┘    │
            │                                       │                 │
            ▼                                       ▼                 │
   ( End of experiment ) ◀── no ──◇ Further change in SDF? ◇── yes ──┘
```
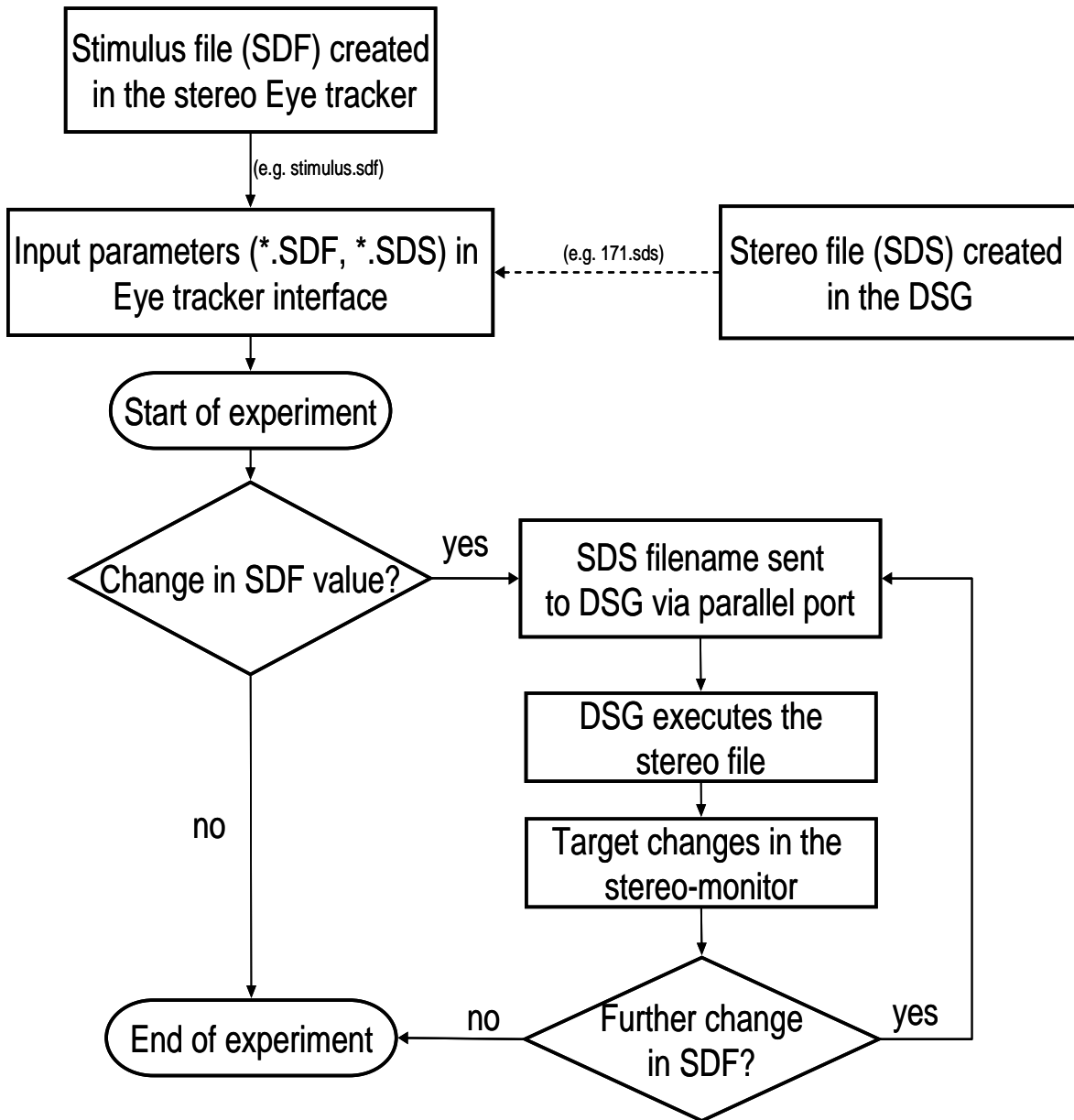
Figure 3.2 Flowchart depicting the cascade of events that take place leading to the display of the stimulus on the stereo-monitor.
The SDS file created in the DSG and the SDF file created in the eye tracker are both initialized at the eye tracker. When stimulus.SDF changes, the corresponding stereo file (171.SDS) is relayed to the computer controlling the DSG. Based on the content of the stereo file, the display on the stereo monitor changes accordingly.

3.2.2 High speed digital infrared photorefractor

3.2.2.1 Milestones in the development of the high speed photorefractor – Effect of light source configurations

The PowerRefractor (Multichannel systems, Germany) has an infrared light source that is positioned eccentrically below the aperture of the CCD camera (in the vertical meridian). Initial tests on this light source configuration showed that the vertical orientation of the photorefractor IR LEDs may not be suitable when this device was intended to be used with the stereo eye tracker. This was because the corneal Purkinje images from the stereo eye-tracker and the IR light source from the PowerRefractor were both aligned in the vertical meridian. Since the PowerRefractor algorithm identifies the brightness profile across the vertical meridian of the pupil, the presence of the two bright corneal Purkinje images in the same meridian (from the eye tracker) would disrupt the photorefraction analysis algorithm causing it to break down. On the other hand, when only LCD goggles were used, without the eye tracker head-set, the pupil diameter and the slope of brightness profiles were detected easily by the PowerRefractor **(Figure 3.3)**. With this result, it was clear that the PowerRefractor and the stereo eye tracker could not be used simultaneously. A new photorefractor and a different light source configuration had to be designed to specifically ensure that the Purkinje images from the stereo eye tracker were ignored when calculating the slope of the brightness profile across the pupil.
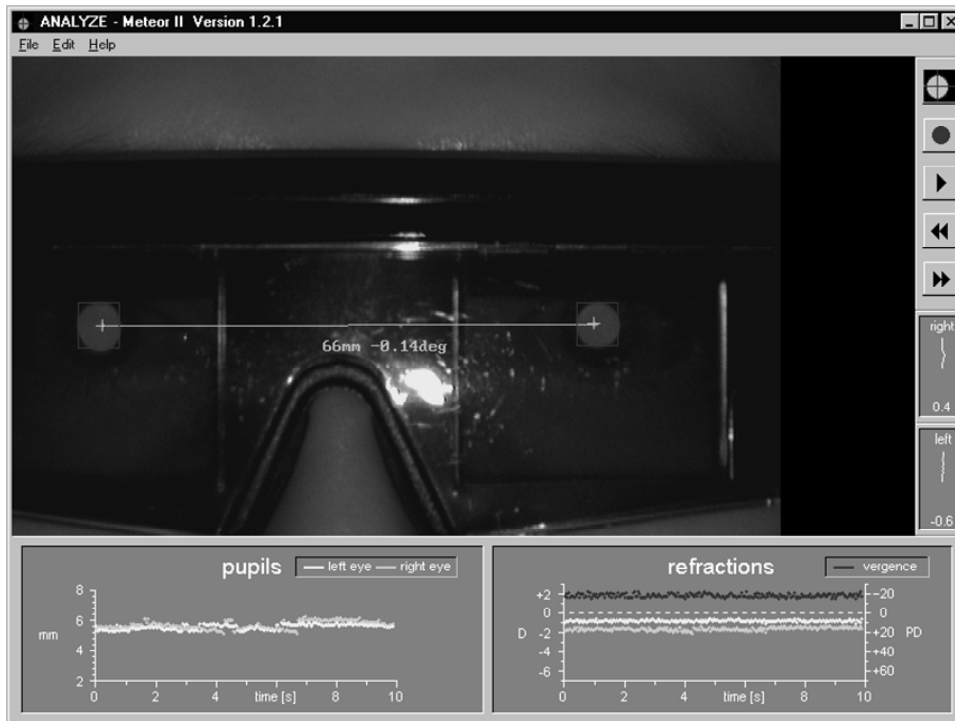
Figure 3.3 Screen shot from the PowerRefractor (binocular mode) through LCS goggles.
When only the LCS goggles are worn by the subject, the brightness profile across the pupil is reliably detected. This shows that although the LCS goggles reduce the overall luminance across the pupil, it was still possible to reliably measure accommodation and pupil dynamics with the PowerRefractor.

3.2.2.2 Hardware – High speed photorefractor

A high speed FireWire infrared CCD camera (QICAM-IR, FAST 1394, QImaging, Canada) was used as the imaging system. The camera was capable of operating up to a sampling rate of 75Hz such that digital images could be captured every 0.0133 seconds. The camera was connected to a pentium-4 computer through the FireWire port. A cluster of infrared LEDs set on aluminium housing was mounted on the camera aperture **(Figure 3.4)**. The design of the LED array allowed the light source could be positioned at any orientation by simply rotating the housing. The orientation of the light source does not

affect the slope of the brightness profile created within the pupil **(Figure 3.5)**. The LEDs

were powered by a DC power source to ensure a continuous light output.

A   B
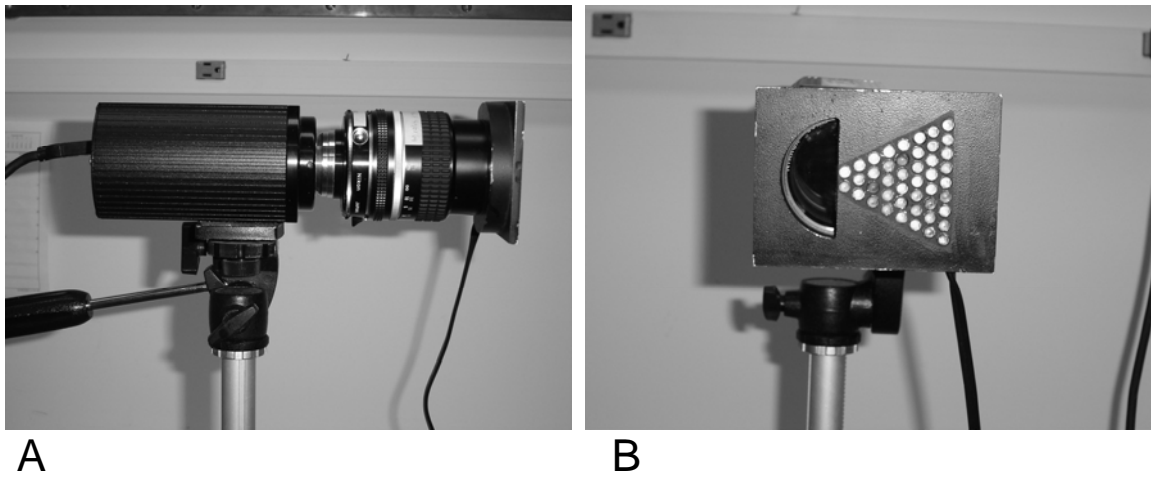
Figure 3.4 High speed infrared photorefractor.
(A) Side view showing the camera and lens housing. The lens housing allowed the camera to be focussed
for any distance between infinity and 80 cms. (B) Front view of the photorefractor. LED lights were housed
on an aluminium board and then mounted on the camera aperture. There are 8 rows of infrared LEDs and a
total of 44 individual LED light sources. The peak wavelength of the LED light source was 895 nm. The
position of the light source can be varied by rotating the aluminium housing. Note that for the high speed
photorefractor the light source was positioned horizontally. The triangular design of the LED light array
was based on previous work in the laboratory (Chad Lehtonen, personal communication).
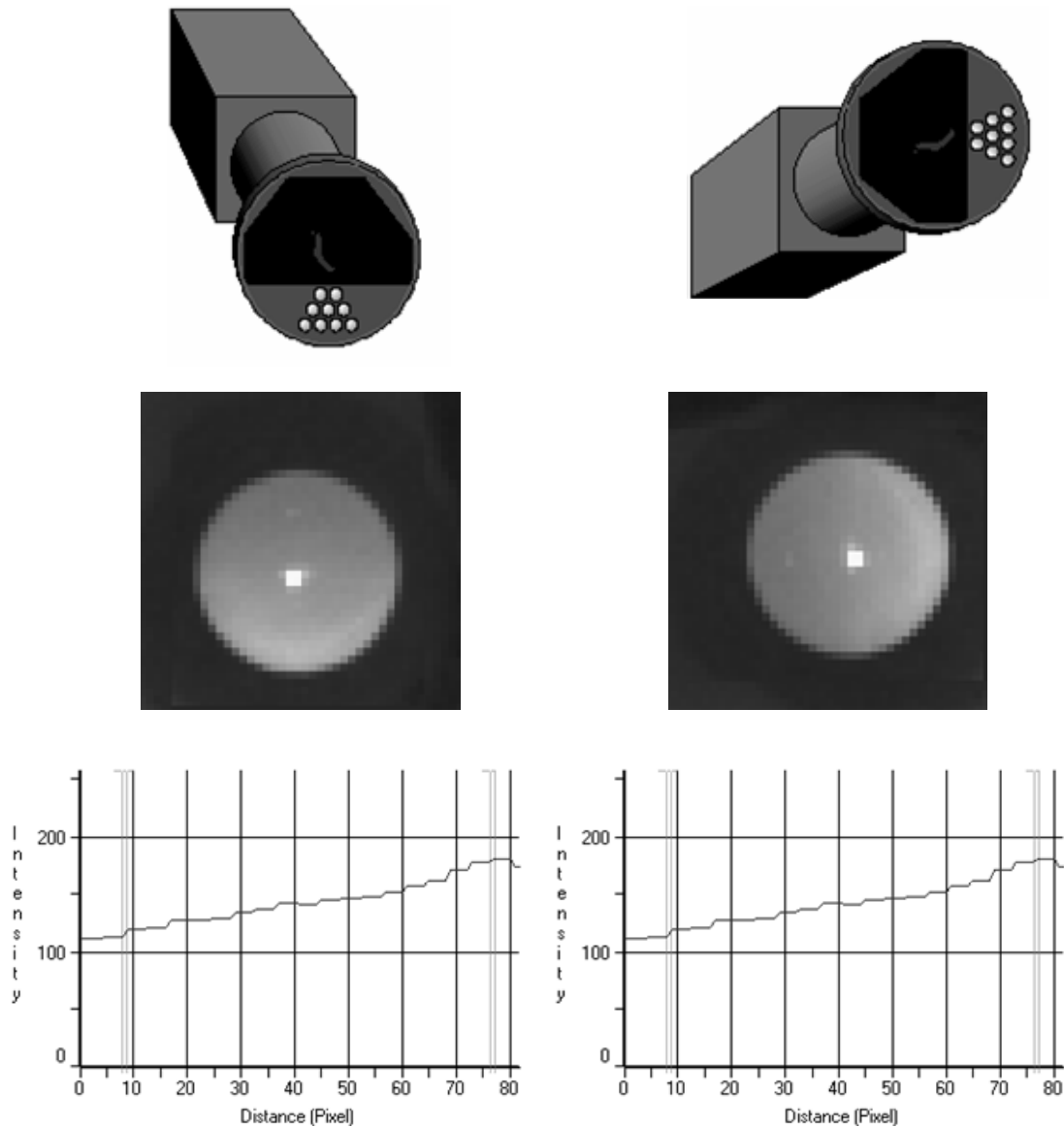
Figure 3.5 Photorefraction brightness profiles as a function of light source position.
The figure shows the brightness profile of a myopic eye with two different light source positions (top). As the position of the light source changes, the brightness profile also changes its orientation (middle). However, the rate of change of the brightness profile (slope) remains the same (bottom graph).

3.2.2.3 Video acquisition and photorefraction analysis

High speed digital video was acquired from the IR camera using commercially available video acquisition software (StreamPix Version 3.13, Norpix Inc. Montreal, Canada). This software served two major functions. First, it allowed for high speed video recording

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from the camera to the computer. The software also saved the video recording as a sequence file which could then be analyzed offline as individual frames **(Figure 3.6)**. Second, during an active video recording, the software allowed for synchronization of the video file (sequence) with other instrumentation (example stereo eye tracker, Badal optometer). The synchronization between the photorefractor and other devices is explained in the next section.

The video sequence file from StreamPix was first converted into an AVI video format and then transferred into an image processing software program (ImagePro Plus, Media Cybernetics, USA) for brightness profile analysis. This program computed the brightness profile across the horizontal meridian of the pupil for each frame in the video file **(Figure 3.6)** exported the gray scale pixel values to EXCEL where a custom written macro calculated the slope (rate of change) of the brightness profile. This process was repeated until all the frames in the video files were analyzed. The slope values for the individual frames were then plotted as a function of their respective capture time. In order to convert the slope values to accommodation (refractive error in one meridian) an individual calibration equation was used. The calibration equation was specific for each subject and represented the conversion from slope (rate of change of pixel brightness across the pupil) to accommodative response. The accommodative response was then plotted as a function of time for analysis of the temporal parameters.
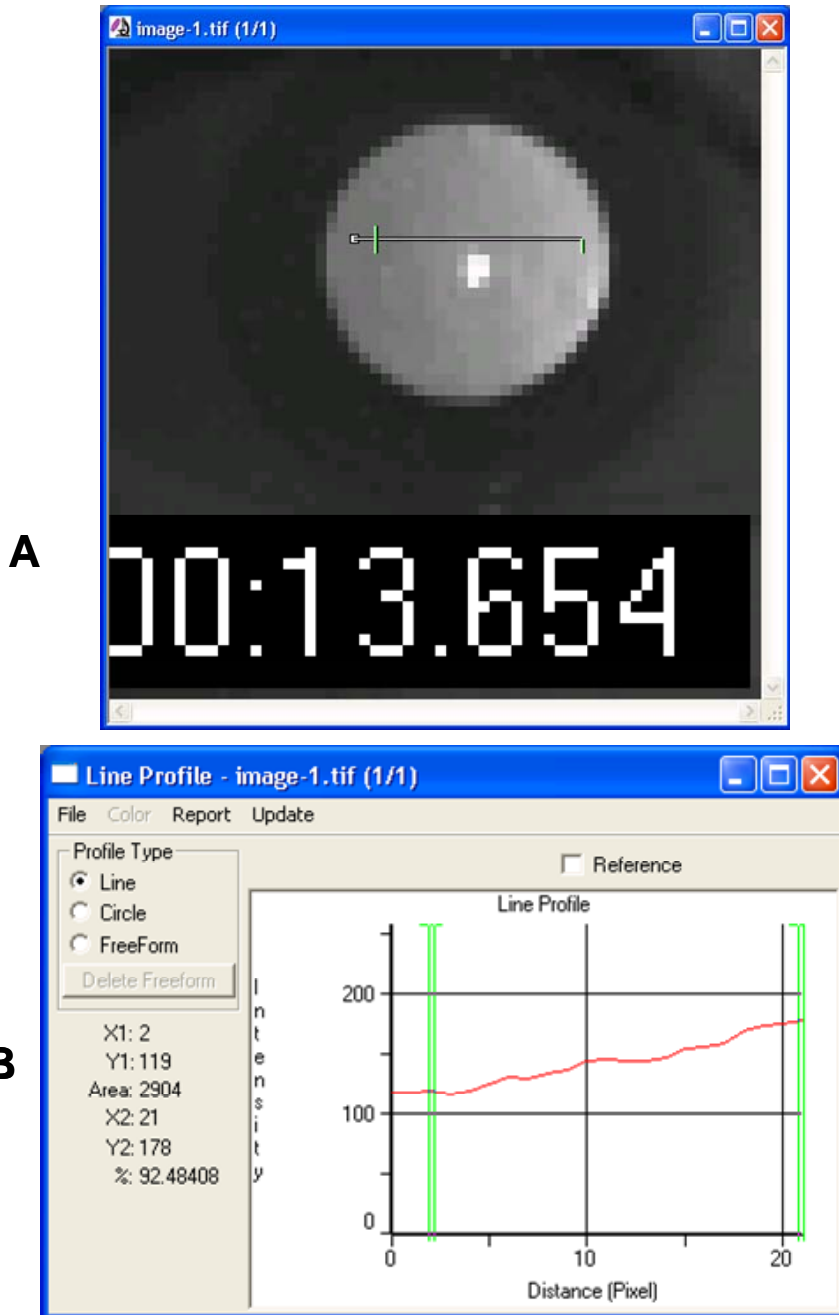
Figure 3.6 Photorefraction analysis of accommodation.
A) Shows the typical brightness profile across the pupil. A horizontal line profile (B) shows a brightness gradient across the pupil. The slope of the brightness profile can be converted to refractive error using a custom calibration equation.

3.2.2.4 Photorefractor calibration

The calibration procedure tested subjects using the same procedure as that outlined in 2.3.2.3. The procedure involved the subject to view a high contrast accommodative target at distance with one eye (example, left eye). An infrared filter (Kodak 87B, IR filter, Rochester, NY) was placed in front of the other eye (right eye), which blocked visible light but allowed the IR light from the photorefractor. Ophthalmic lenses (in ±0.50-D steps up to a range of ±4 D) were placed in front of the right eye (the eye with the filter) to induce refractive error. The intensity profiles on the pupil changed linearly with different lenses in front of the eye. The slope of the brightness profile (Y) for each lens was then plotted as a function of the induced refractive error (X; ophthalmic lenses from 0 to 4 D). The data were fit with a linear regression and the equation represented the *refraction equation* for that subject. The refraction equation was characteristic for each subject and allowed the conversion of the slope of the brightness profile across the pupil to accommodative response (refractive error along the horizontal meridian).

3.2.3 Synchronization of the high speed photorefractor, stereo eye tracker and DSG

In order to mark the stimulus onset on the photorefractor it was synchronized with the stereo eye tracker and DSG. The synchronization process was set up such that the photorefractor would receive a signal from another device (example stereo eye tracker) and mark the reception of the signal on the video interface along with time stamp information. The time stamp information was essential because it would allow the

examiner to assess when the synchronization signal was received within the duration of the video recording.

An input/output (I/O) control box was designed which copied the signals sent from the eye tracker to the DSG (section 3.2.1.1) and relayed this information to the photorefractor **(Figure 3.7)**. A custom written software plug-in (NI6503 – PCI, National Instruments Inc, USA) (Eye Catcher, StreamPix, Norpix Inc. Canada) in the photorefractor detected the incoming signal and marked it on the video interface during the video recording **(Figure 3.8)**. An important technical requirement was that the incoming signal had to last for at least 3 video frames duration (sampling interval). For example, if the signal (stimulus onset) from the DSG/eye tracker had to be synchronized with the photorefractor operating at 60Hz, then the signal had to be present for at least 3 frames or 50 msecs ([1/60] * 3) when it reached the photorefractor computer. In order to ensure that this requirement was met, the I/O control box had a built in duration enhancer which maintained the signal transmission for the required duration while the synchronization between the stereo eye tracker and the photorefractor took effect.

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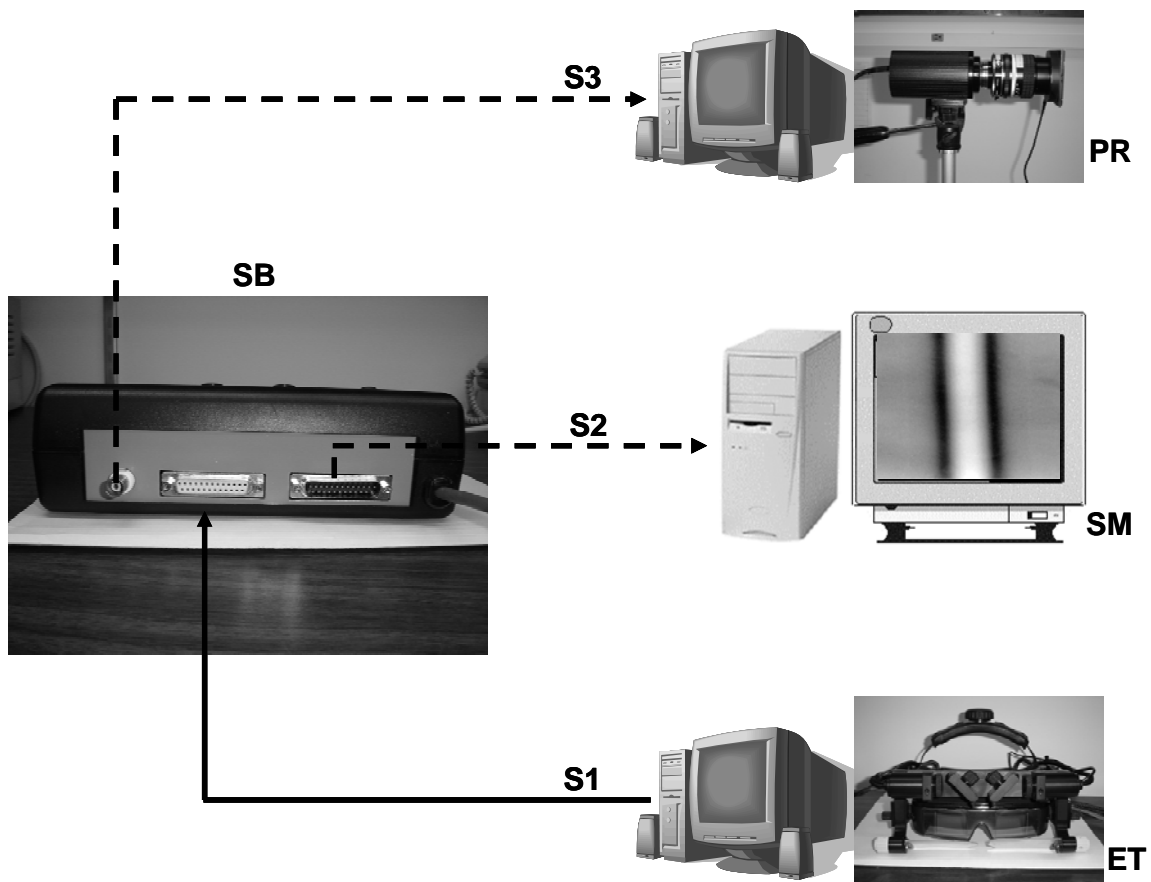
Figure 3.7 Synchronization of the stereo eye tracker, DSG and the photorefractor.
The stereo eye tracker (ET) sends the information (S1) through the parallel port of its computer to the synchronization box (SB). The information received by the eye tracker is copied by SB and sent as S2 and S3 to both the DSG stereo monitor (SM) and the photorefractor (PR) respectively. Once the signal is received by the DSG the stimulus changes to the difference of Gaussian target. The photorefractor also marks the onset of this signal (S3) on its video interface. The whole process gets repeated during the next stimulus onset. The signal file (S1) in the eye tracker has the information about when and how many times this synchronization process should take place.

A   **B**
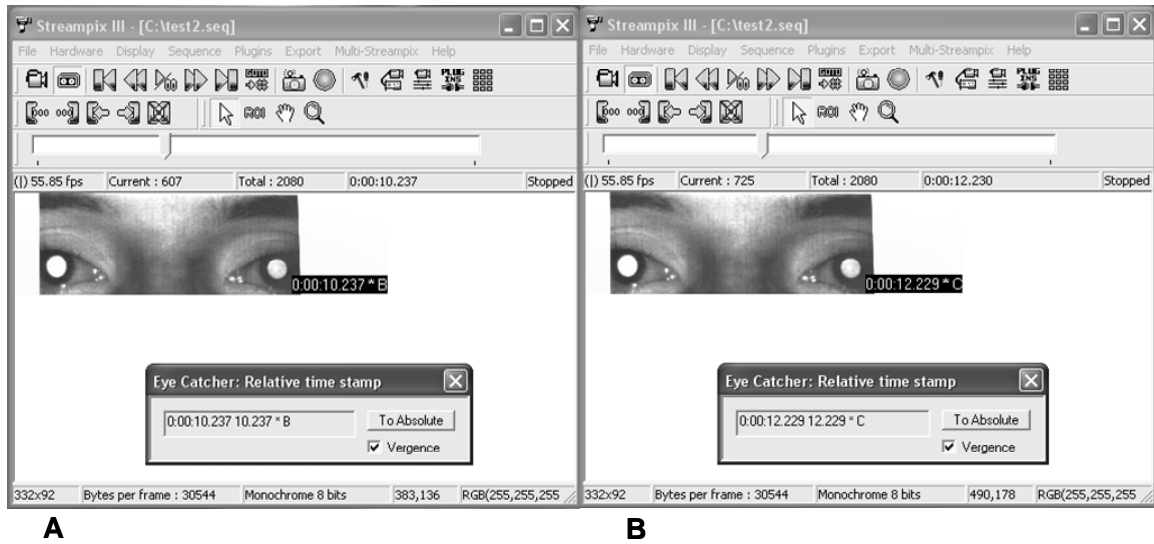
Figure 3.8 Screen shot of the photorefractor interface showing the synchronization of the signal from the eye tracker.

The video interface incorporates a custom written software plug-in *(inset in the figure)* that monitors for the external signal during the video recording. Once the signal is detected, it is marked along with the time stamp information in the video frame. The marking on the video frame starts with B (baseline) **[3.8A]** for the first signal information received and toggled between B and C (convergence) **[3.8B]** thereafter. Each signal received lasted for three video frames. The software plug-in also generated a TIME file that has a complete list of time and frame numbers when the signal was received during the video recording. The creation of the TIME file allowed for the synchronization information to be quickly reviewed during playback.

3.3 Methods

3.3.1 Subjects

Six subjects (mean age = 25±1.37 yrs) were involved in the study. All subjects had a best corrected visual acuity of at least 6/6 in each eye and normal binocular vision. Refractive errors were estimated by objective non-cycloplegic retinoscopy and spherical equivalents were found to range from -0.25 to +0.75D. Informed consent for participation was obtained from all participants prior to their involvement in the study. The study was approved by the Office of Research Ethics at the University of Waterloo.

3.3.2 Experimental set-up and Procedure

The investigation involved two separate sessions. In the first session, the dynamics of blur driven accommodation were measured using the Badal system and the high speed photorefractor. During the second session, the stereo eye tracker/DSG assembly was used in synchrony with the high speed photorefractor to obtain dynamic measures of vergence-accommodation. All subjects participated in both the sessions. The sessions were conducted on separate days and the order of sessions was randomized between the subjects.

3.3.2.1 Session 1 – Assessment of blur driven accommodation dynamics with the high speed photorefractor

The experimental paradigm was similar to the protocol used earlier in **Chapter 2 (section 2.3.2.2)** for the measurement of monocular blur driven accommodation where the high speed photorefractor was substituted for the PowerRefractor. The accommodative targets were two high contrast (black on white) vertical lines that were back illuminated by white LEDs. The far target was held constant at the focal point of the 5D Badal lens while the near target was placed at different distances between the Badal lens and the far target to create the appropriate accommodative demand. The accommodative responses were recorded by the photorefractor set a distance of 1m (sampling rate of 75Hz). During the experiment, the left eye of the subject was occluded with an eye patch and all measures were obtained from the right eye. The accommodative demand in the Badal optometer was set to range from 1 – 2.5D in 0.5D steps. The near target was first set to a 1D stimulus demand and then subsequently moved to other positions (closer to the Badal

lens) for higher accommodative demands. The subject watched the targets in the Badal optometer as they were alternately illuminated. The specific onset time of the near / far stimulus was randomized to avoid prediction. While the subjects accommodated to see the targets presented within the Badal system, the photorefractor continuously recorded a video file onto the computer. The high speed photorefractor was synchronized with the stimuli (far and near targets) in the Badal optometer such that a change from far to near (or near to far) was event-marked on the interface of the video sequence. The video was analyzed offline frame by frame using image analysis software (ImagePro Plus, Version 5.1, Media Cybernetics, California). All subjects included in the study were individually calibrated and the calibration equations for each subject allowed for the conversion of the slope of the brightness profile to refractive error. Four trials were conducted across each of the stimulus amplitudes (1, 1.5, 2 and 2.5D). The individual responses to each stimulus demands were averaged and analyzed separately as far to near (accommodation) and near – far (dis-accommodation) responses.

3.3.2.2 Session 2 – Measurement of vergence and vergence-accommodation dynamics

Disparity vergence was measured using the stereo eye tracker / disparity stimulus generator (DSG) assembly. A non-accommodative target (0.2cpd difference of Gaussian target) was presented in crossed disparity demands of 2 to 5 degrees in 1 degree steps on a stereo monitor set at a distance of 1.2 meters. The vergence response of the eye was measured continuously by the head mounted stereo eye tracker at a sampling rate of 120Hz. Four trials were performed for each stimulus demand. The transition from

baseline (0 degree) to crossed disparity constituted a disparity ON paradigm while the transition from 2 degree back to baseline constituted the disparity OFF paradigm. All disparity stimulus demands were programmed as an asymmetrical vergence paradigm with the stimulus aligned to the left eye. Binocular eye position was continuously monitored by the stereo eye tracker during both stimulus transitions (disparity ON and disparity OFF). While vergence response was monitored by the stereo eye tracker the synergistic accommodative response was measured using the high speed photorefractor (sampling rate of 60Hz). The photorefractor obtained video recordings of the subjects left eye through the LCS goggles of the eye tracker. The onset of the stimulus on the stereo monitor was synchronized with the high speed photorefractor and the eye tracker. The video files obtained by the photorefractor were analyzed offline. The analysis of vergence-accommodation was similar to the analysis used for blur accommodation responses **(section 3.2.2.3, Figure 3.9 and Figure 3.10)**.
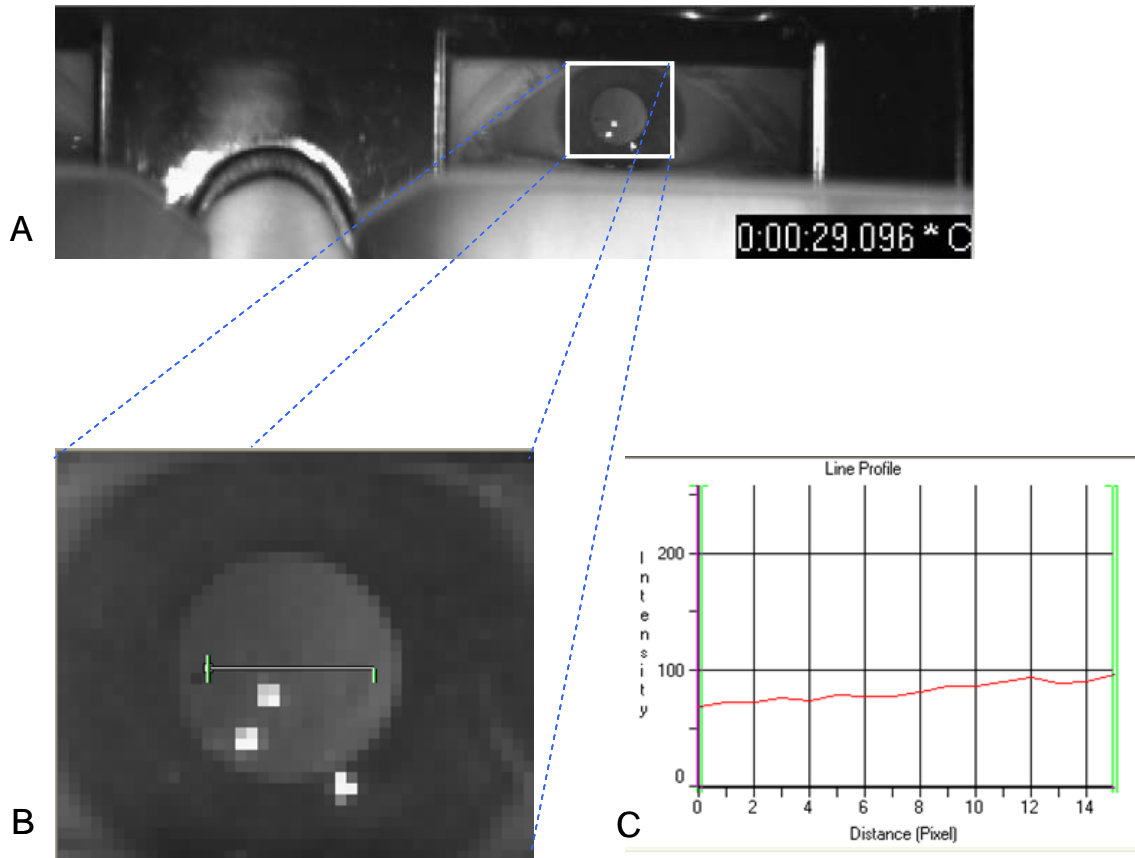
Figure 3.9 Analysis of accommodation responses through the LCS goggles of the eye tracker showing the first frame at the onset of the disparity ON paradigm.

A). Screen shot of the video recording by the photorefractor. The resolution of the image was 332 * 92 pixels. The video was recorded at a sampling rate of 60Hz. Although the photorefractor could sample faster than 60Hz the LED light source from the eye tracker was powered by an AC source thereby limiting the maximum sampling rate of the video frame to 16.66 msecs (60Hz). During the analysis, the left eye of the subject was first selected by defining an AOI (area of interest) shown in the figure by the square outline. B) The AOI was then separated from the rest of the image and a line profile of the greyscale pixel brightness was obtained. C) The plot of the brightness profile showing a positive slope of increasing pixel brightness across the pupil from left to right. These brightness values were exported for each frame to EXCEL where a custom designed macro allowed for its conversion to accommodative response.
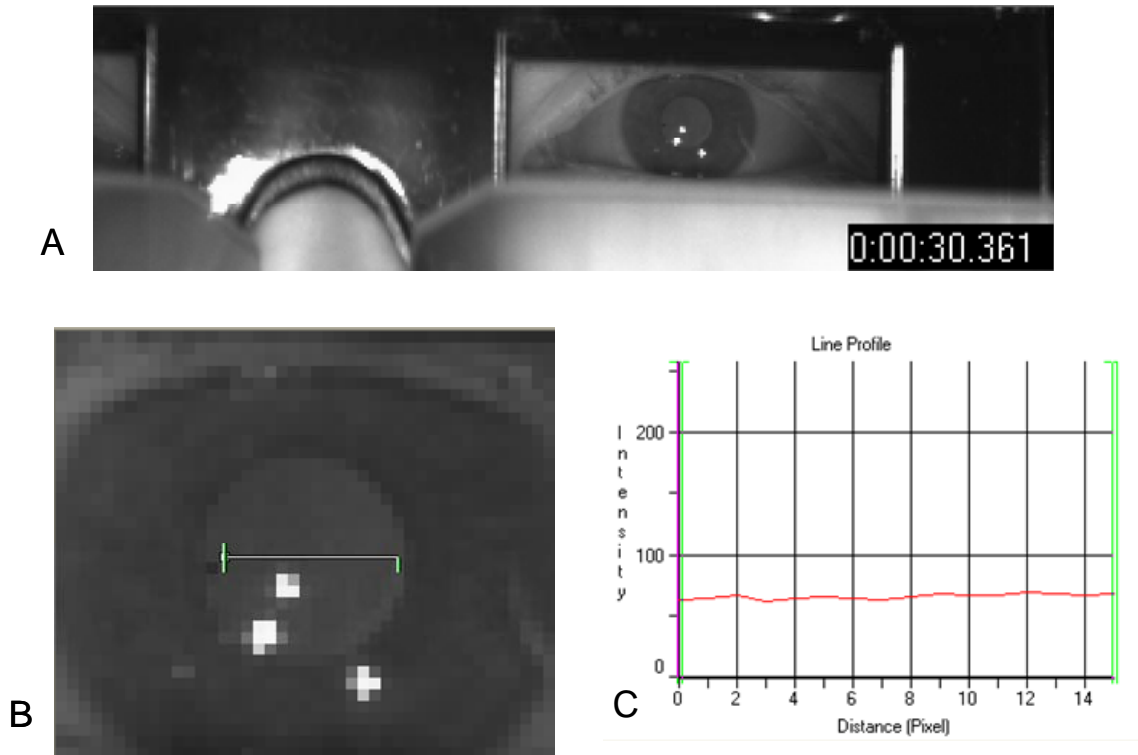
Figure 3.10 Analysis of accommodation through the eye tracker.
The figure shows the change in brightness profile across the pupil 1.26 seconds after the onset of the disparity ON stimulus. Note that the brightness profile across the pupil (B) has changed in its slope. The horizontal luminance profile is relative flatter (C) compared to the slope observed at the start of the stimulus demand. The change in this slope value was converted to refractive error using the calibration equations. By orienting the light source on the photorefractor to the horizontal meridian, the corneal Purkinje images from the eye tracker located in the vertical meridian of the pupil (B) are avoided.

3.4   Analysis of the accommodation and vergence responses

The averaged accommodation and vergence responses from session 1 and session 2 at each stimulus demand were analyzed using statistical and graphics software (Origin Pro, Version 7, Origin Labs Inc., California) to obtain the temporal parameters. The same analysis procedure was used for the analysis of blur accommodation, vergence-accommodation and disparity vergence. To avoid repetition the analysis is explained below for blur accommodation responses only.

3.4.1 Obtaining the temporal parameters of the response

Accommodative position responses were plotted across time. Velocity (D/s) and Acceleration (D/s^2) were computed by differentiating the position response using a two point differentiating algorithm. The position response and the differentiated velocity and acceleration profiles were all smoothed using a 5 point Fast Fourier Transform (FFT) smoothing function. This resulted in smoothed position data, smoothed velocity and smoothed acceleration profile. These traces were then analyzed separately to obtain the various dynamic parameters.

The start and end co-ordinates of the accommodative response were identified by a velocity threshold criterion. The algorithm has been used earlier in marking the onset and completion of saccadic eye movements (Irving, Goltz, Steinbach, & Kraft, 1998) and a similar approach has also been described for the identification of the onset and end of an accommodative response (Schor, Lott, Pope, & Graham, 1999). Complete details on this procedure are provided in **Appendix 1**. The start and end of the accommodative response detected by the threshold algorithm were also inspected by eye (manually). The magnitude of the accommodative response between the start and end co-ordinates was computed and defined as the response amplitude. Also, the time difference between the start and end of the accommodative response was defined as the movement time.

Several dynamic parameters were assessed from the smoothed velocity and acceleration profiles. **Table 3.1** provides a list of all these parameters and their definitions. The response parameters are also illustrated in **Figure 3.11**. The main sequence (amplitude

vs. peak velocity relationship) was plotted for each subject separately for accommodation and dis-accommodation.

Parameter (units)	Definition
Latency (msecs)	Time difference between onset of stimulus and onset of response
Movement time (msecs)	Time difference between the onset of the response and the end of the response
Amplitude (D or degrees)	The difference in the accommodation (or vergence) position between the start and end of the response
Peak Velocity (D/s or degrees/s)	The highest velocity attained in the velocity profile
Time to peak velocity (msecs)	The time taken to attain peak velocity after the response onset
Peak Acceleration (D/s^2 or degrees/s^2)	The highest acceleration attained in the acceleration profile
Duration of Acceleration (msecs)	The time taken to increase acceleration from response onset and decrease acceleration back to $0D/s^2$
Skewness ratio	The ratio of the time to peak velocity and movement time of the accommodative response
Slope of the velocity profile * (D/s^2 or degrees/s^2)	The rate of change of velocity between response onset and peak velocity

Table 3.1 Definition of the response parameters.
The slope of the velocity profile (*) was measured exclusively for monocular blur driven accommodation only. The units are indicated as dioptre (D) or degrees depending on the system (accommodation or vergence) studied.
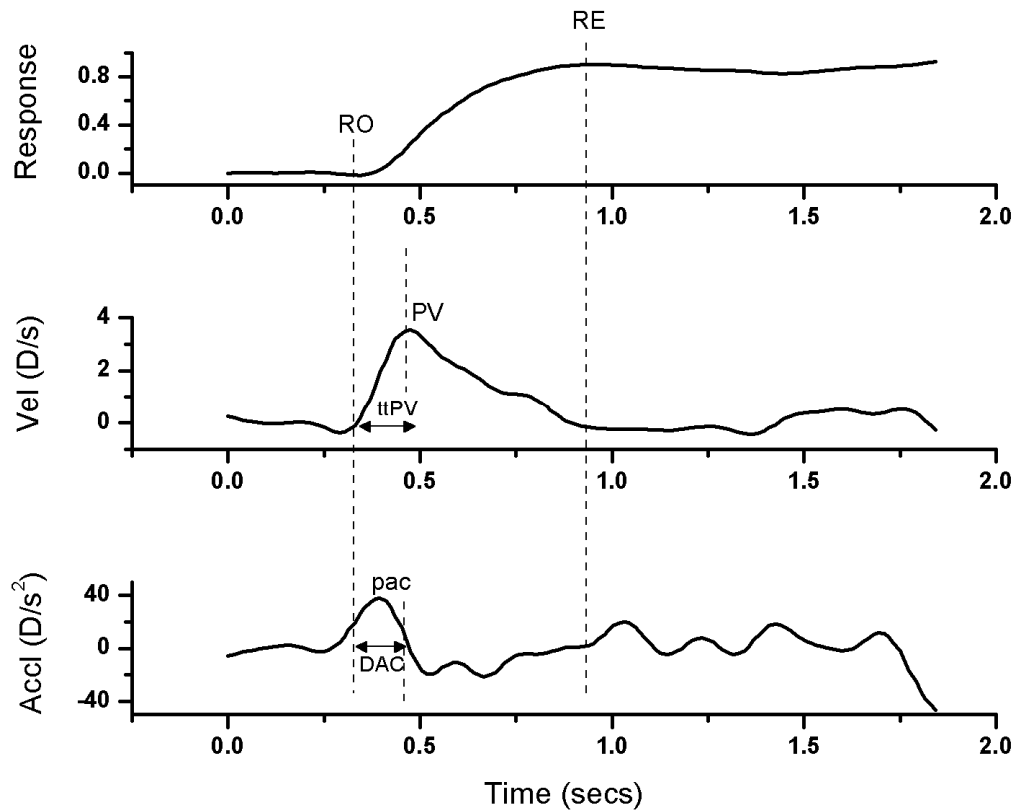
Figure 3.11 Example of an accommodative response and its associated velocity and acceleration profile. RO and RE indicate the response onset and response end respectively. The temporal parameters measured from the velocity (middle) and acceleration (bottom) profiles are identified in the figure. PV and ttPV refer to the peak velocity (D/s) and the time to peak velocity (msecs) respectively. For the acceleration profile (bottom), PAC and DAC indicate the peak acceleration (D/s^2) and duration of acceleration (msecs) respectively.

3.5 Results

3.5.1 Subjects

Of the six subjects enrolled in the study, one subject (S2) reported difficulty in fusing the targets and could not complete session 2. Hence, the results on session 2 (vergence and vergence-accommodation) were summarized for the remaining 5 subjects. On the other hand, all six subjects completed session 1 of the study.

3.5.2 *Calibration of the high speed photorefractor*

Figure 3.12 shows the calibration data from the high speed photorefractor for all the 6 subjects. It can be observed that the relationship between lens power (X) vs. slope of the brightness profile (Y) changed linearly for all the subjects. The data could be fitted by a linear regression (R^2 values range from 0.97 – 0.99). All the fits were statistically significant. Therefore the slope of the intensity profile across the eye could be used to provide information about the refractive state in the vertical meridian (accommodation). This method is identical to photorefractive calibrations adopted by previous studies (Vilupuru & Glasser, 2002; Kasthurirangan, Vilupuru, & Glasser, 2003). While theoretical relationships predict photorefractive calibrations to change with pupil size, empirical studies have confirmed photorefractive calibrations to be robust for pupil sizes between 4 to 7.8mm (Choi, Weiss, Schaeffel, et al. 2000) and this range is similar to the pupil diameters of the subjects in the current study. At very low pupil diameters (< 3mm), the precision of photorefraction is affected because there are fewer pixels to define the slope of the brightness profile and less amount of light returning from the eye (Choi, Weiss, Schaeffel, et al. 2000). All subjects enrolled in the study had pupil diameters greater than 4.5mm OU and the mean change (decrease) in pupil diameter between the calibration study and the empirical study was found to be 0.6mm.
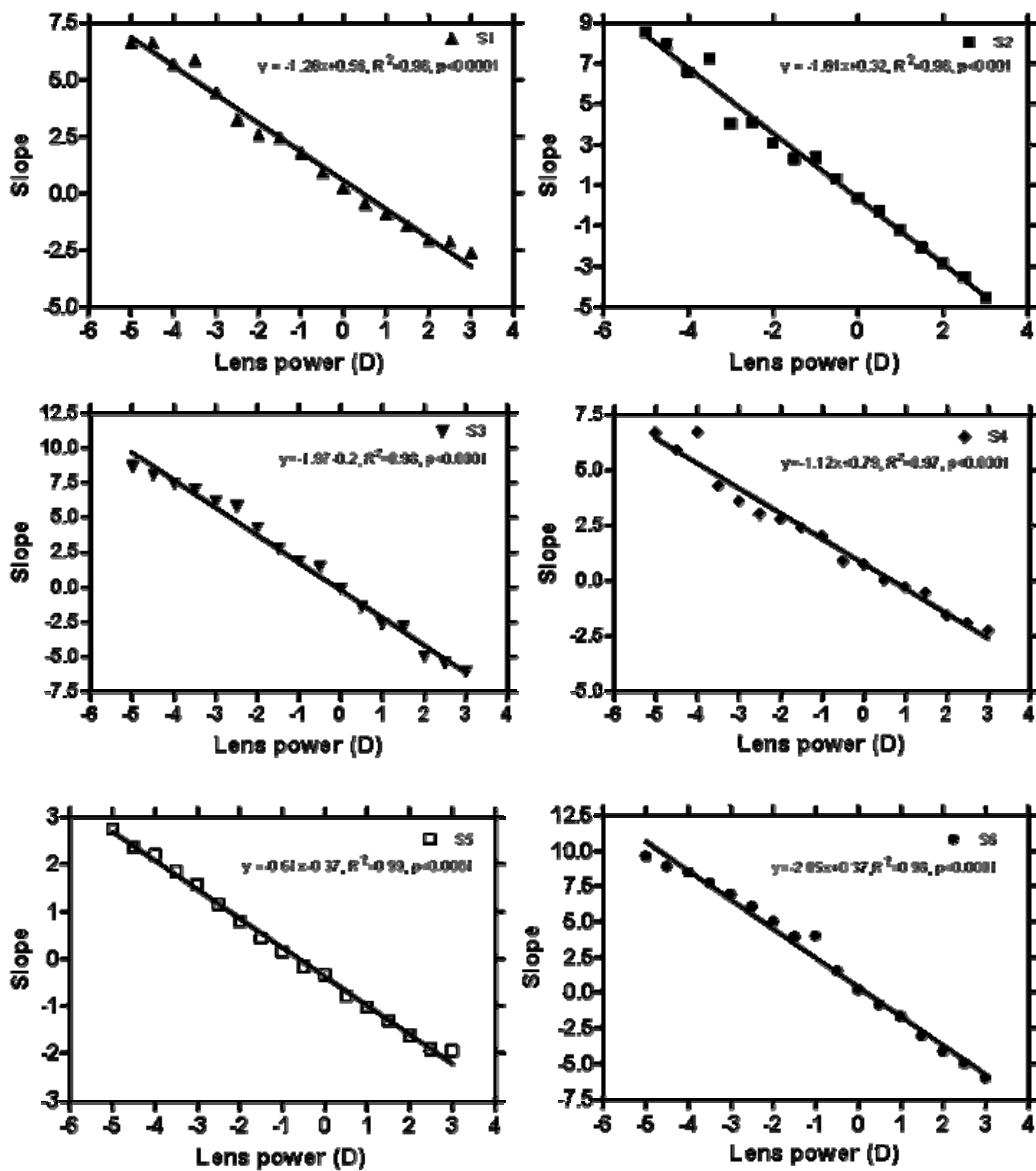
Figure 3.12 Calibration plots from the high speed photorefractor for the 6 subjects.
Linear regression equations for all subjects were statistically significant. The equations were characteristic for each subject and converted the slope of the brightness profile to refractive error.

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3.5.3   Session 1 - Dynamics of monocular blur driven accommodation

3.5.3.1 General Dynamics

An averaged smoothed response of monocular blur driven (far to near) accommodation and (near to far) dis-accommodation is shown in **Figure 3.13**.
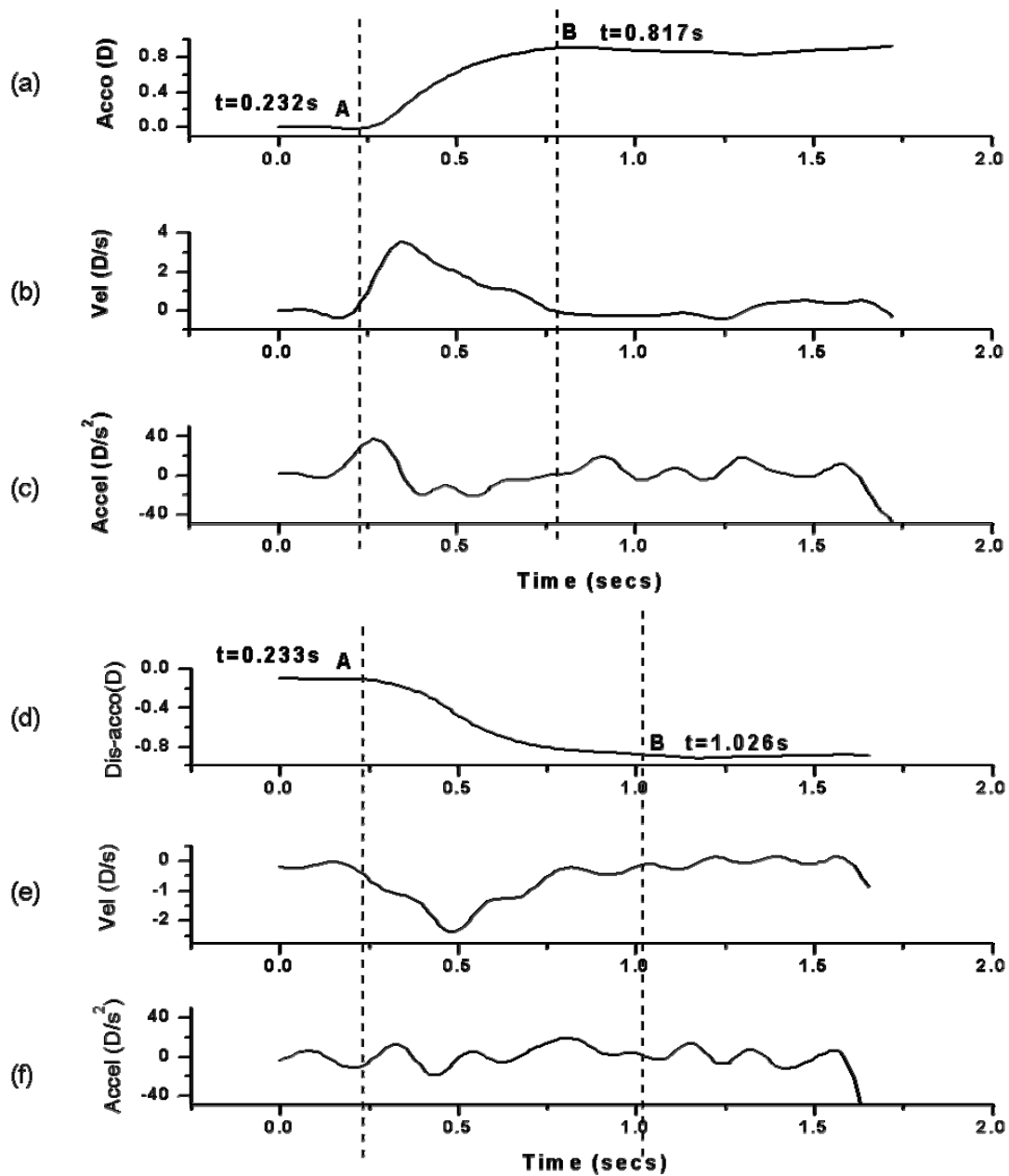
Figure 3.13 Dynamic responses of monocular blur driven accommodation and dis-accommodation. The stimulus was a 1D step input presented within a Badal optometer. The velocity and acceleration profiles for accommodation (b, c) and dis-accommodation (e, f) are also shown.

3.5.3.2 Main sequence relationship

The amplitudes vs. peak velocity relationships for accommodation and dis-accommodation are shown in **Figure 3.14**. The individual slope, intercept and R^2 values for each of the six subjects for accommodation and dis-accommodation are shown in **Table 3.2**. These results show that the accommodation and dis-accommodation dynamics are amplitude dependent. Both accommodation and dis-accommodation showed statistically significant linear relationships across the range of amplitudes tested (Accommodation, $y = 2.55x + 0.65$, $R^2 = 0.55$, $p<0.0001$; Dis-accommodation, $y = 2.66x + 0.50$, $R^2=0.65$, $p<0.0001$). Statistical comparison of the linear regression functions (amplitude vs. peak velocity) for accommodation and dis-accommodation showed no significant difference between the slope or the intercept values (slope comparison, $F_{(1,44)} = 0.026$, $p = 0.87$; Intercept comparison, $F_{(1,45)} = 0.008$, $p = 0.92$).
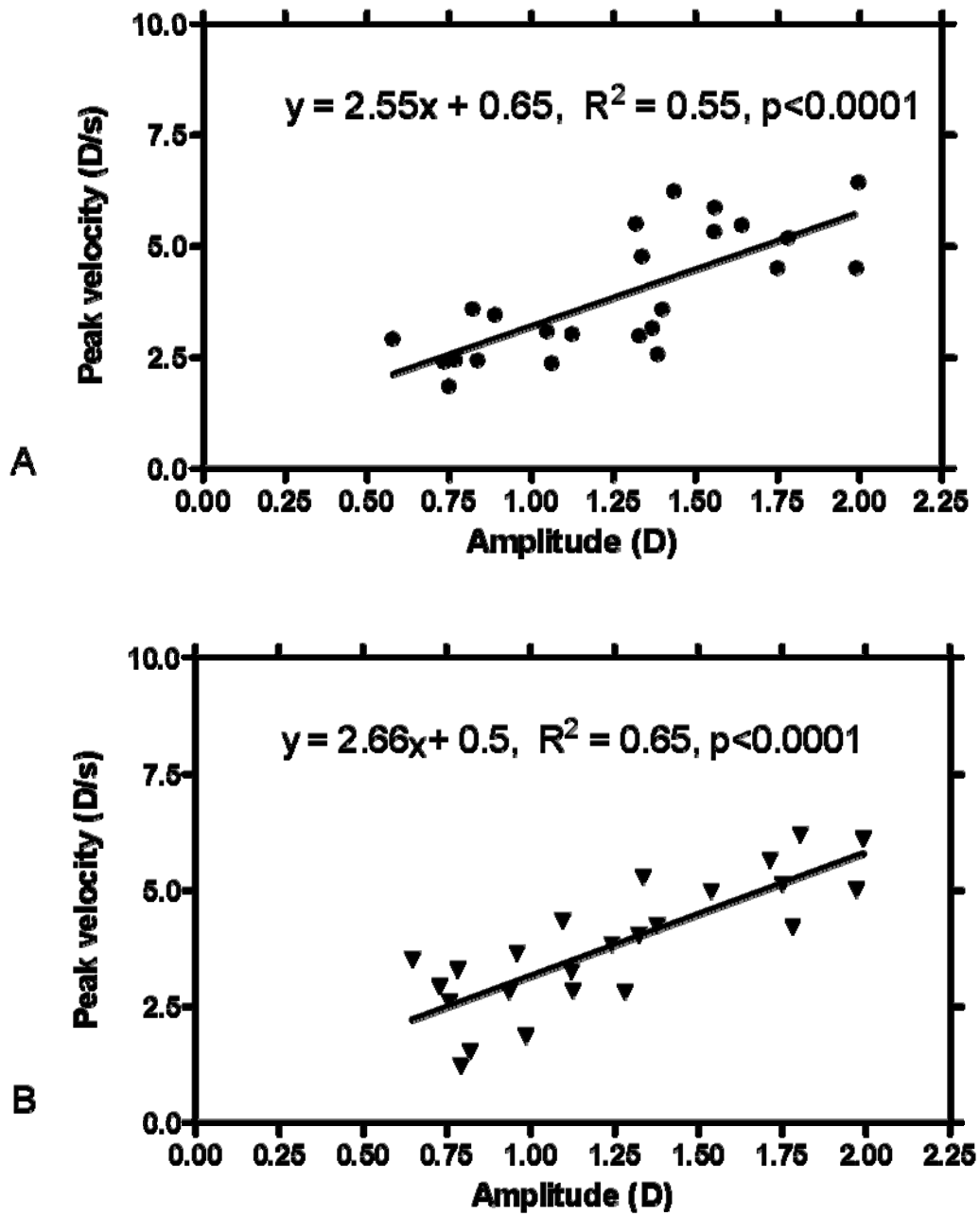
Figure 3.14 Amplitude vs. peak velocity relationship for accommodation and dis-accommodation. Accommodation (A) and dis-accommodation (B) show a linear relationship for the range of amplitudes tested. The slope of linear regression for accommodation and dis-accommodation are also very similar.

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Subjects	Accommodation			Dis-accommodation		
	Slope	Intercept	R^2 value	Slope	Intercept	R^2 value
S1	2.28	1.95	0.90	2.96	0.31	0.98
S2	2.66	0.62	0.72	2.99	-0.78	0.91
S3	2.11	0.32	0.69	2.78	-0.67	0.95
S4	2.13	0.31	0.96	2.54	1.17	0.78
S5	2.49	0.38	0.86	2.03	1.51	0.67
S6	3.19	1.01	0.90	2.47	1.54	0.51
MEAN±SD	**2.48±0.41**	**0.77±0.64**	**0.84±0.11**	**2.63±0.36**	**0.51±1.05**	**0.80±0.18**

Table 3.2 Individual slope, intercept and R^2 values for the linear regression functions (amplitude vs peak velocity) of accommodation and dis-accommodation.

3.5.3.3 Accommodation vs. Dis-accommodation

In order to investigate the differences in the temporal parameters as a function of various response amplitudes, the accommodation and dis-accommodation responses were separated into different amplitude bins (0.5 - 1, 1 – 1.5, 1.5 - 2 D) and the temporal parameters were compared using a two-way ANOVA with Bonferroni post-tests. The results are shown in **Table 3.3 and Figure 3.15**. The overall comparisons using two-way ANOVA showed that, regardless of the response amplitude most of the temporal parameters (with the exception of movement time) were similar between accommodation

and dis-accommodation (**Table 3.3**). Bonferroni post-tests results showed that for each amplitude bin all response parameters were similar between accommodation and dis-accommodation.

Parameter	Accommodation	Dis-accommodation	ANOVA p value
Latency (msecs)	240.46±80.56	247.55±80.88	0.934
Movement time (msecs)	843.25±222.02	1016.78±279.82	0.002
Time to peak velocity (msecs)	192.45±61.91	209.42±91.55	0.139
Peak Acceleration (D/s^2)	47.76±20.59	47.56±20.76	0.344
Duration of Acceleration (msecs)	196.10±68.66	186.52±97.71	0.765
Skewness	0.25±0.07	0.25±0.10	0.597
Slope of the velocity profile (D/s^2)	25.81±12.71	21.03±19.23	0.194

Table 3.3 Average values (± 1 SD) of the temporal parameters for accommodation and dis-accommodation. All parameters (with the exception of movement time) were similar between accommodation and dis-accommodation.
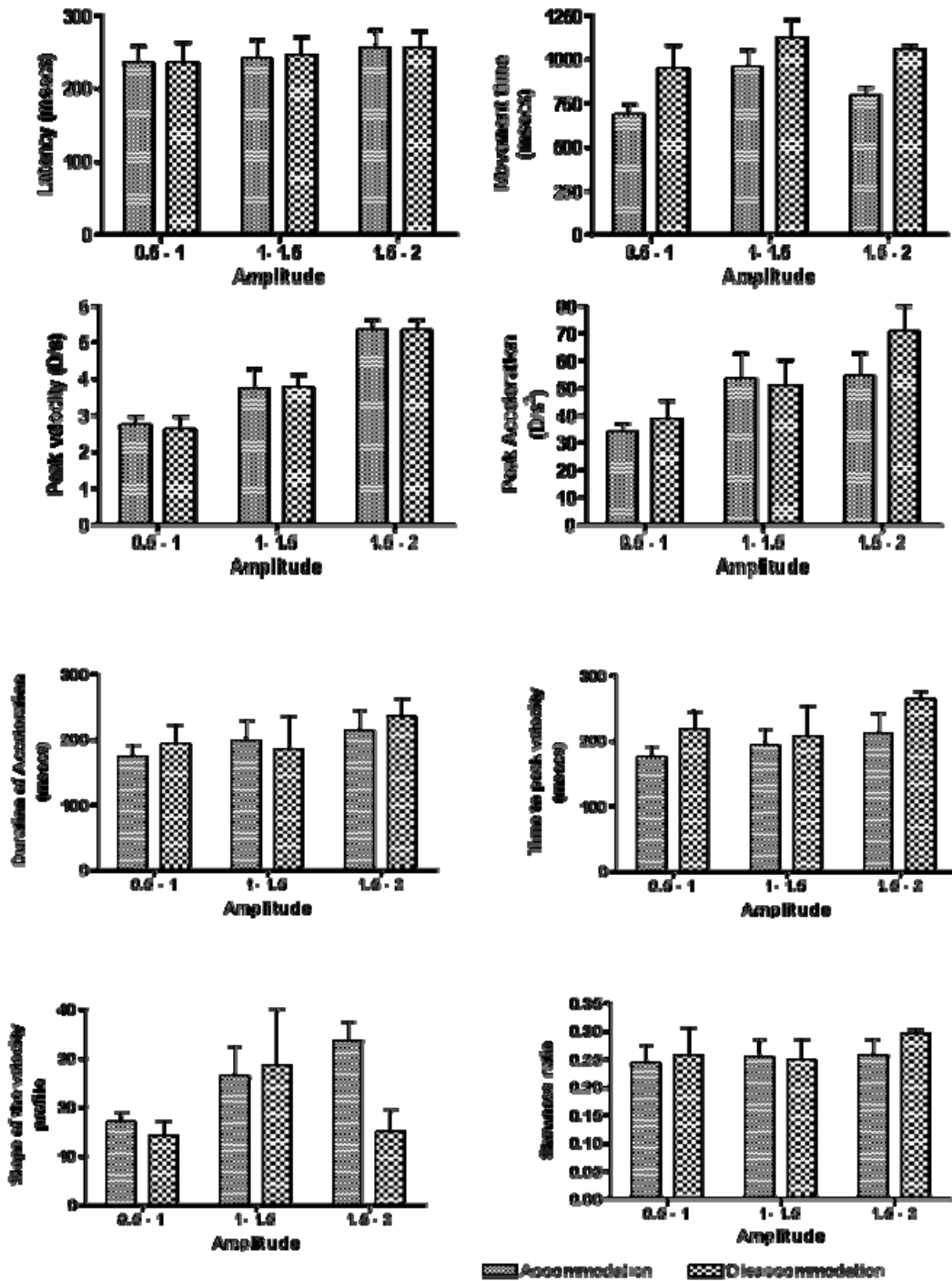
Figure 3.15 Comparison of the response parameters between accommodation and dis-accommodation across different amplitude bins.
For each amplitude bin (Mean±SEM), the response parameters were similar between accommodation and dis-accommodation. There was no statistical difference (two-way ANOVA, Bonferroni post-test, p>0.05)

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3.5.4 Session 2 - Dynamics of disparity vergence and vergence-accommodation

3.5.4.1 VA/V ratio

The mean values for the stimulus and response VA/V ratios were 0.13±0.05 D/Δ and 0.15±0.09 D/Δ respectively. Although the response VA/V ratio was slightly higher then the stimulus measure, the mean difference between the two was not statistically significant (student t test, p>0.05).

3.5.4.2 General Dynamics

A typical result of disparity vergence and vergence-accommodation to step change in stimulus during disparity ON and disparity OFF paradigms is shown in **Figures 3.16 and 3.17** respectively. In both cases vergence-accommodation changed with disparity vergence. On an average, the VA response was found to start 92.24±47.23 msecs after the onset of disparity vergence. The average values (±1 SD) of all the dynamic parameters for vergence and VA during the disparity ON and OFF paradigms are summarized in **Table 3.4**. Overall, the dynamic parameters were similar between disparity vergence and vergence-accommodation with the exception of peak velocity and peak acceleration. Disparity vergence had significantly greater velocity and acceleration compared to vergence-accommodation.
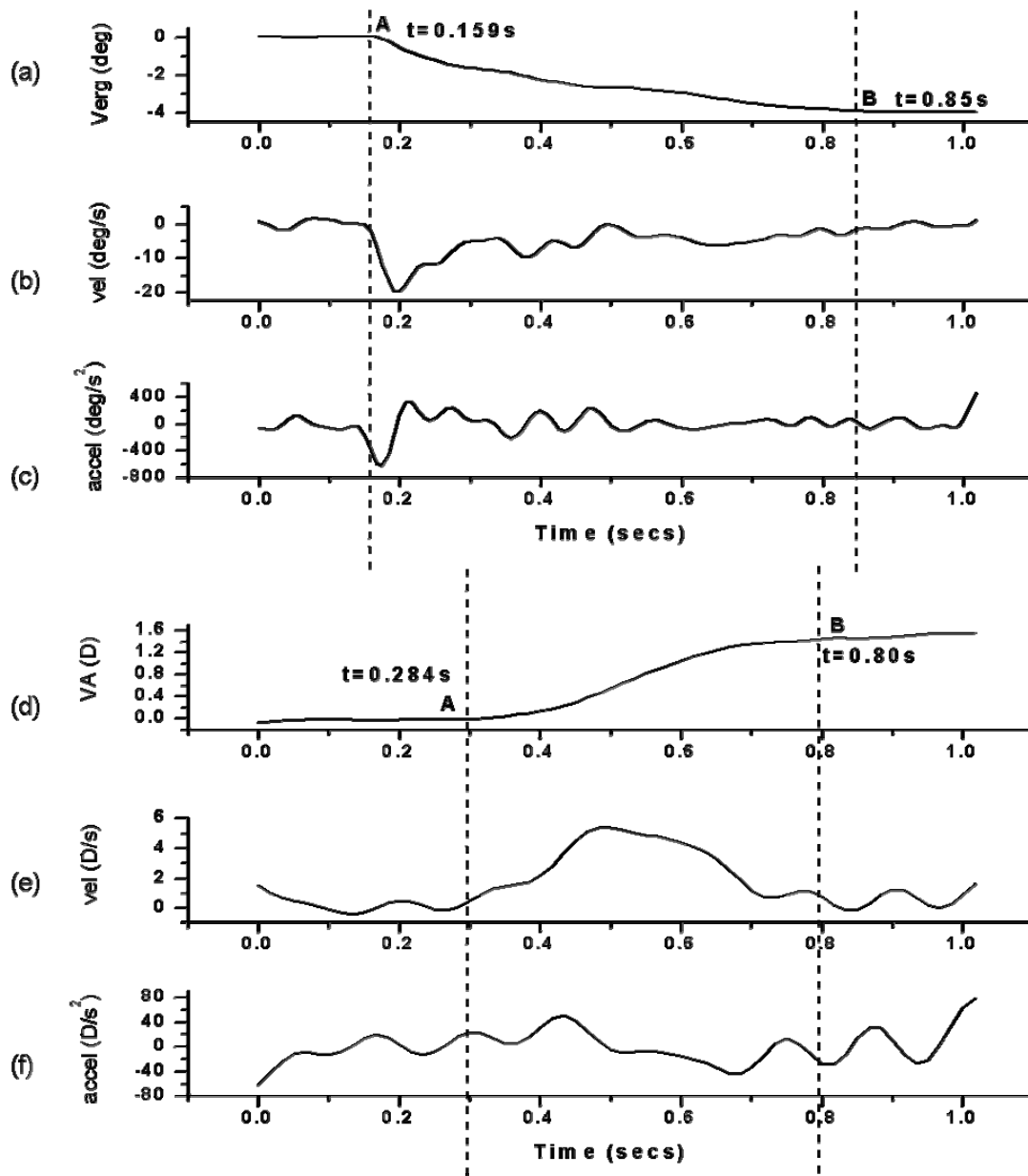
Figure 3.16 Typical responses of disparity vergence and vergence accommodation during the disparity ON paradigm.
The stimulus changed as a 4 degree disparity step. Convergence is indicated by a downward deflection (a) while increase in vergence-accommodation is indicated by an upward deflection (d). The velocity and acceleration profiles for vergence (b, c) and vergence-accommodation (e, f) are also shown.
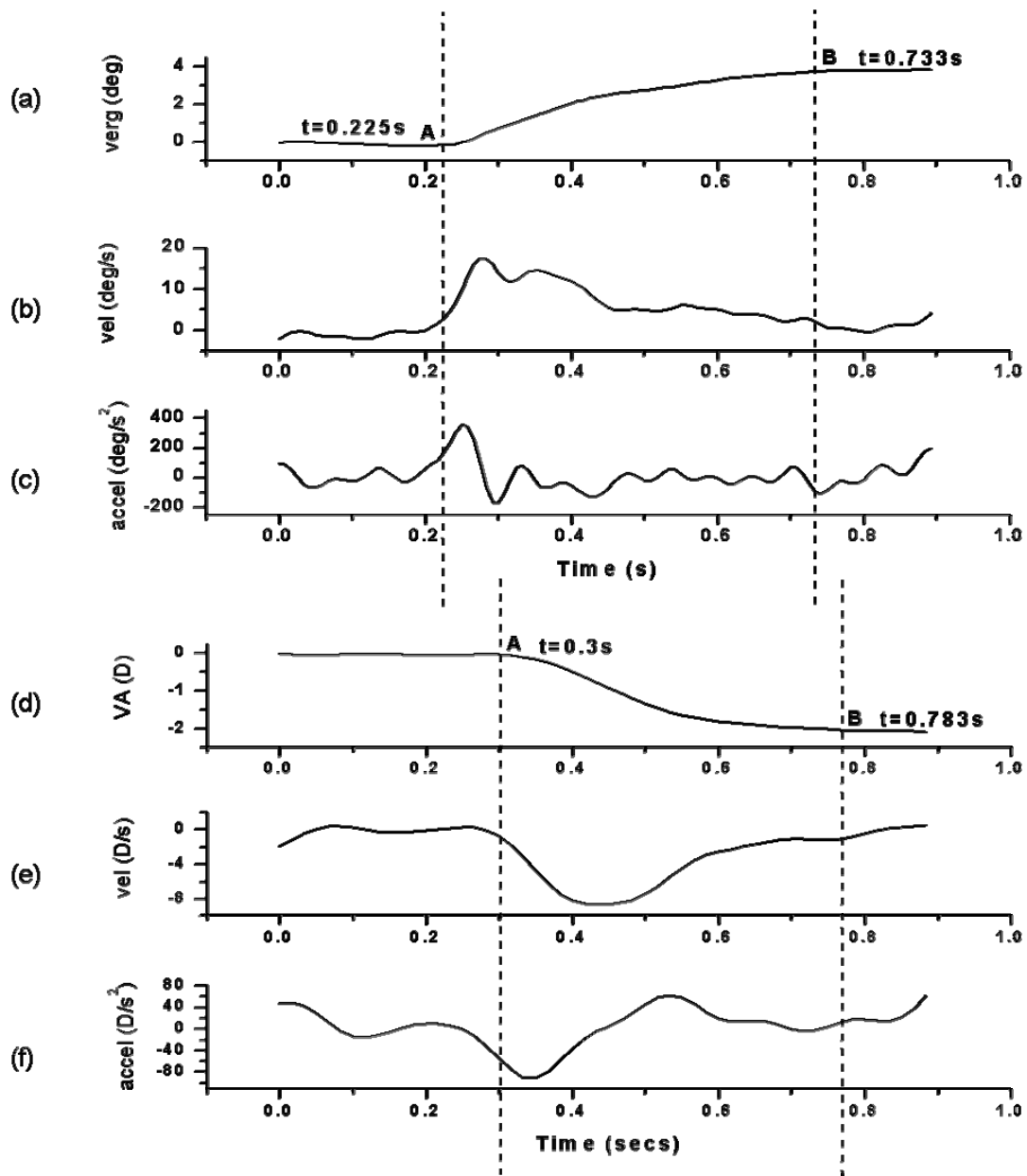
Figure 3.17 Typical responses of disparity vergence and vergence-accommodation during the disparity OFF paradigm.
The stimulus changed as a step demand of 4 degrees (disparity OFF). The velocity and acceleration profiles of vergence (b, c) and vergence-accommodation (e, f) are also shown.

Parameter	Disparity ON		Disparity OFF	
	VA	Vergence	VA	Vergence
Latency (msecs)	282±80.46	192.16±64.05	287.55±62.92	192.11±43.33
Movement time (msecs)	673.58±381.63	726.58±295.22	607.55±405.08	575.33±270.41
Peak Velocity*	3.24±2.10 (D/s)	17.43±10.74 (Deg/s)	3.76±2.35 (D/s)	21.93±9.62 (Deg/s)
Peak Acceleration*	27.68±20.96 (D/s^2)	295.24±179.31 (Deg/s^2)	31.87±20.85 (D/s^2)	560.27±514.53 (Deg/s^2)
Duration of Acceleration (msecs)	153.92±42.13	151.5±97.37	177.37±66.54	167.87±76.31
Time to peak velocity (msecs)	148.5±40.51	152.25±100.56	172.44±64.51	168.87±74.71
Skewness	0.28±0.13	0.24±0.15	0.31±0.08	0.30±0.16

Table 3.4 Average values (± 1 SD) of the dynamic parameters for vergence and VA during disparity ON and disparity OFF paradigms.
With the exception of Peak acceleration all temporal parameters were statistically similar between vergence and vergence-accommodation. peak velocity and peak acceleration were significantly greater for vergence (* $p<0.05$) when compared to vergence accommodation.

3.5.4.3 Main sequence relationship

The amplitude vs. peak velocity relationship for disparity vergence and vergence accommodation is shown in **Figures 3.18 and 3.19** respectively. For the range of response amplitudes studied, disparity vergence and vergence-accommodation both tend to show a statistically significant linear relationship ($p<0.05$). There was no difference in the linear regression function (slope, intercept) between disparity ON and disparity OFF

for disparity vergence or vergence-accommodation (Disparity vergence: slope comparison, $F_{(1, 36)}=0.06$, p=0.79; Intercept comparison, $F_{(1,37)}=3.84$, p=0.06; Vergence-accommodation: slope comparison, $F_{(1,36)}=1.67$, p=0.20; Intercept comparison, $F_{(1,37)}=1.90$, p=0.17). Disparity vergence and vergence-accommodation were equally fast between disparity ON and disparity OFF paradigms. The VA responses were also divided into different amplitude bins and the peak velocity across each bin was compared between disparity ON and disparity OFF using a two-way ANOVA with Bonferroni post-tests. The results are shown in **Table 3.5**. The statistical results showed that VA response was equally fast during disparity ON and disparity OFF across all the amplitude bins.
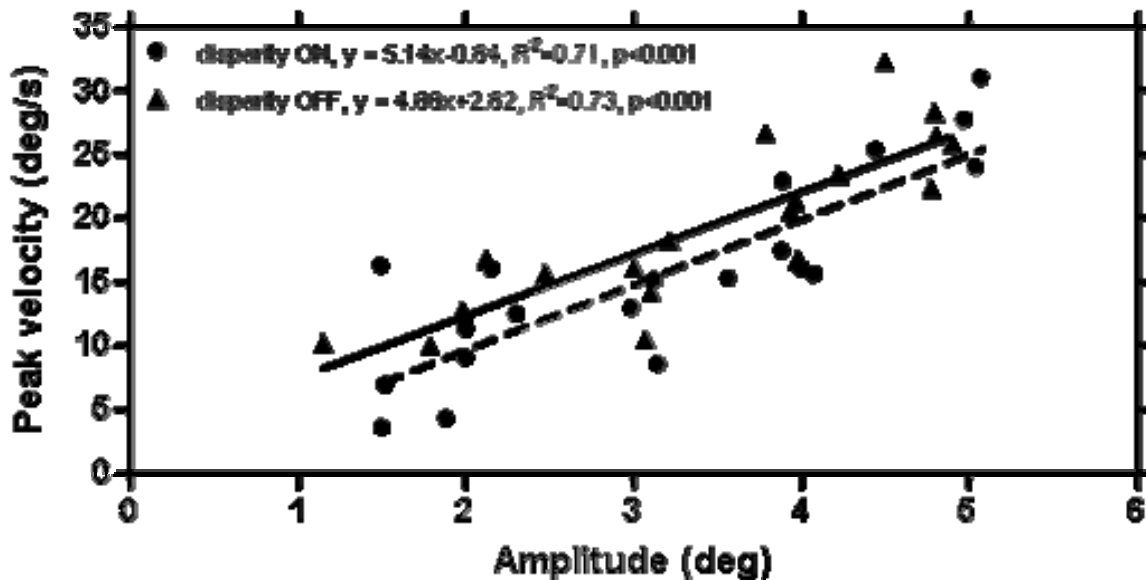
Figure 3.18 Amplitude vs. peak velocity plot for vergence responses during disparity ON and disparity OFF.
Both responses show a statistically significant linear relationship. The slope of disparity ON (dashed line) and disparity OFF (solid line) were similar.
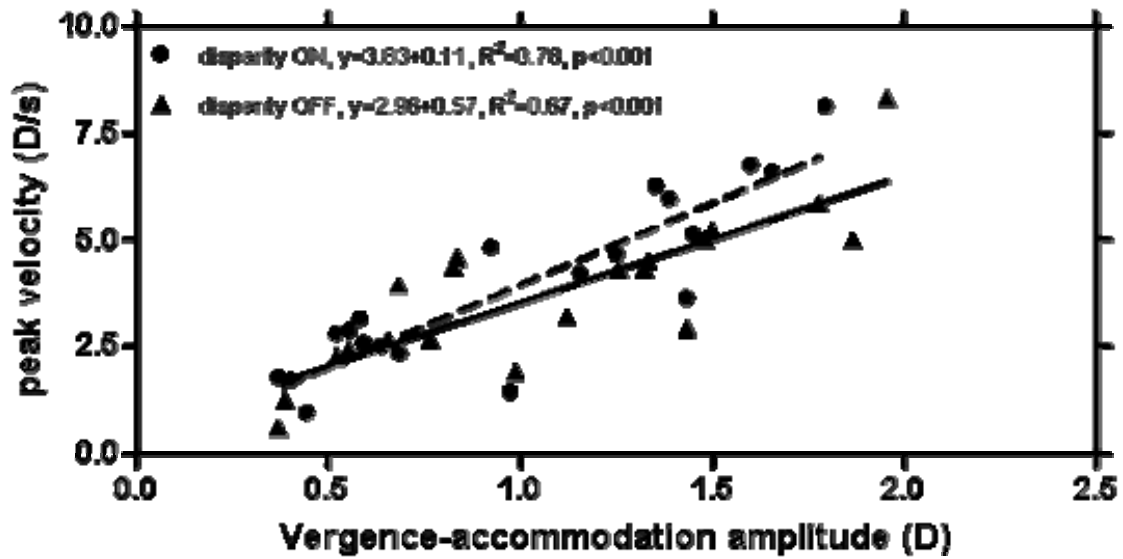
Figure 3.19 Amplitude vs. peak velocity relationship for VA during disparity ON and disparity OFF. The slope of VA during disparity ON (dashed line) and disparity OFF (solid line) were similar.

Amplitude	Disparity ON	Disparity OFF	Difference	95% CI of diff.	t	P value
0.5-1	2.36	2.91	0.55	-2.34 to 3.44	0.49	P > 0.05
1-1.5	4.79	2.93	-1.85	-4.74 to 1.03	1.65	P > 0.05
1.5-2	8.13	6.72	-1.41	-4.30 to 1.48	1.26	P > 0.05

Table 3.5 Comparison of peak velocity of VA across different amplitude bins.
Two-way ANOVA with Bonferroni post-tests showed that the peak velocity of VA was similar between disparity ON and disparity OFF across all the amplitude bins.

3.5.4.4 Vergence-accommodation during disparity ON and disparity OFF paradigms

To compare the parameters of vergence-accommodation between disparity ON and disparity OFF paradigms, the response amplitudes of vergence-accommodation were

matched and the temporal parameters were compared between the two paradigms. Comparisons were done by a two-way ANOVA with Bonferroni post-tests (**Figure 3.20**). Overall, when combined across both amplitudes, the response parameters for vergence-accommodation were similar during disparity ON and disparity OFF ($p>0.05$ for all response parameters during both paradigms). Hence, direction of vergence does not appear to influence the dynamics of vergence-accommodation. Bonferroni post-tests also showed that for each amplitude bin, the response parameters for vergence-accommodation were similar for disparity ON and disparity OFF.
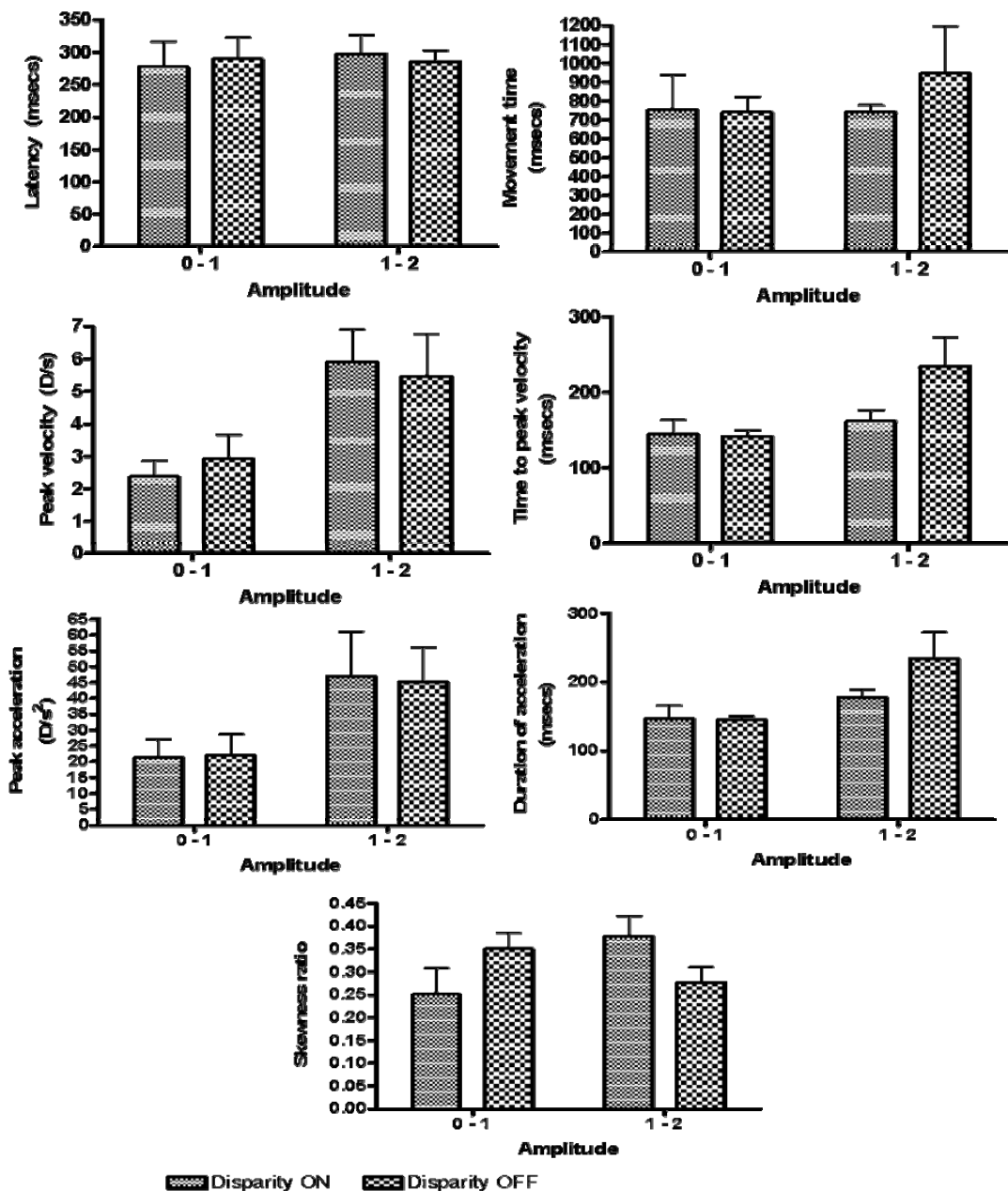
Figure 3.20 Dynamic parameters of vergence-accommodation during disparity ON and disparity OFF paradigms.
The response amplitudes of vergence-accommodation were matched and the parameters were compared using two-way ANOVA and Bonferroni post-tests between disparity ON and disparity OFF across two amplitude bins (Mean±SEM). No statistical difference was found for any of the parameters between the disparity ON and disparity OFF. For each amplitude bin, vergence-accommodation had similar dynamic parameters between disparity ON and disparity OFF (two-way ANOVA, Bonferroni post-tests).

3.5.5 *Session 1 vs. Session 2 - Comparison of dynamic parameters between disparity vergence, vergence-accommodation and blur accommodation*

The response parameters of vergence, vergence-accommodation and blur-accommodation were compared to each other for the five subjects who completed both sessions of the study.

3.5.5.1 Blur accommodation vs. Disparity accommodation

In order to compare the dynamics of monocular blur driven accommodation and binocular vergence-accommodation, the amplitudes of the two responses were matched and the various temporal parameters were compared between the two responses. The temporal parameters were individually compared across two amplitude bins namely 0 – 1D and 1 – 2D. Vergence-accommodation during disparity ON was compared to accommodation and vergence-accommodation during disparity OFF was compared to dis-accommodation. Two-way ANOVA with Bonferroni post-tests was performed to compare the temporal parameters between VA and blur accommodation. Overall, there was no statistical difference in any of the response parameters between vergence-accommodation and blur-accommodation. This result applied for both disparity ON and disparity OFF paradigms. Post-test results for the two amplitude bins also showed no difference in any of the response parameters **(Table 3.6 to 3.9)**. The results collectively show that, when response amplitudes are matched, the dynamic parameters of vergence-accommodation and blur-accommodation are similar. Hence, open-loop and closed loop accommodation appear to have similar dynamics.

Parameter	0 – 1 D		1 – 2 D	
	VA (ON)	BA (Acco)	VA (ON)	BA (Acco)
Latency (msecs)	277±87.93	232±74.55	297±65.04	260±75.55
Peak Velocity (D/s)	2.35±1.13	2.72±0.62	5.9±2.25	4.38±1.34
Movement time (msecs)	751.77±413.49	681±151.94	839±84.04	897.33±218.56
Peak acceleration (D/s^2)	21.26±13.04	33.77±7.67	46.96±31.53	53.36±21.62
Duration of Acceleration (msecs)	146±44.69	174.40±42.06	177.66±25.42	203.33±75.29
Time to peak velocity (msecs)	144.22±43.33	174.40±42.06	161.33±34.42	198.46±67.38
Skewness	0.25±0.12	0.24±0.07	0.37±0.10	0.25±0.07

Table 3.6 Comparison of the response parameters between vergence-accommodation (during disparity ON) with blur accommodation.
The response parameters were compared using a two-way ANOVA with Bonferroni post-tests. The results indicate that all the temporal parameters were similar between VA and blur accommodation. There was no statistical difference ($p>0.05$).

Parameter	Disparity ON VA vs. Blur accommodation					
	Amp	VA	BA	Diff	t	p
Latency (msecs)	0 - 1	277	232	-45	0.96	>0.05
	1 - 2	297	260	-37	0.79	>0.05
Peak Velocity (D/s)	0 - 1	2.36	2.72	0.36	0.10	>0.05
	1 - 2	5.90	4.38	-1.52	0.41	>0.05
Movement time (msecs)	0 - 1	751.80	681	-70.78	0.45	>0.05
	1 - 2	839	897.3	58.33	0.37	>0.05
Peak Acceleration (D/s^2)	0 - 1	21.26	33.77	12.51	0.15	>0.05
	1 - 2	46.96	53.37	6.41	0.07	>0.05
Duration of Acceleration (msecs)	0 - 1	146	174.4	28.4	0.62	>0.05
	1 - 2	177.7	203.3	25.67	0.56	>0.05
Time to peak velocity (msecs)	0 - 1	144.2	174.4	30.18	0.66	>0.05
	1 - 2	161.3	198.50	37.13	0.81	>0.05
Skewness	0 - 1	0.25	0.24	-0.01	0.09	>0.05
	1 - 2	0.37	0.25	-0.12	1.58	>0.05

Table 3.7 Tabular results from two-way ANOVA for the comparison of vergence-accommodation (disparity ON) and accommodation.
Results show that all response parameters were similar between vergence-accommodation (disparity ON) and blur accommodation

Parameter	0 – 1 D		1 – 2 D	
	VA (OFF)	BA (Disacco)	VA (OFF)	BA (Disacco)
Latency (msecs)	288.83±75.39	250.33±75.45	285±40.11	248.22±42.11
Peak Velocity (D/s)	2.91±1.68	2.60±0.87	5.45±2.92	4.52±1.07
Movement time (msecs)	839±185.38	945.44±328.2	5.45±2.92	4.52±1.07
Peak acceleration (D/s^2)	839±185.38	945.44±328.2	944.66±561.04	1081±226.23
Duration of Acceleration (msecs)	144.66±13.55	192.66±75.23	233.66±86.31	181±118.29
Time to peak velocity (msecs)	141.83±17.45	217.77±68.35	233.66±86.31	201.9±111.71
Skewness	0.34±0.07	0.25±0.12	0.27±0.07	0.25±0.08

Table 3.8 Comparison of the response parameters between vergence-accommodation (disparity OFF) and blur dis-accommodation.
The response parameters were compared by two-way ANOVA and were found to be similar between VA and blur dis-accommodation. There was no statistical difference in any of the response parameters.

Parameter	Disparity OFF VA vs. Blur dis-accommodation					
	Amp	VA	BA	Diff	t	p
Latency (msecs)	0 - 1	288.8	250.3	-38.5	1.15	>0.05
	1 - 2	285	248.2	-36.77	1.11	>0.05
Peak Velocity (D/s)	0 - 1	2.91	2.6	-0.31	0.08	>0.05
	1 - 2	5.45	4.52	-0.93	0.26	>0.05
Movment time (msecs)	0 - 1	839	945.4	106.4	0.52	>0.05
	1 - 2	944.7	1081	136.3	0.67	>0.05
Peak Acceleration (D/s^2)	0 - 1	21.93	38.75	16.82	0.09	>0.05
	1 - 2	45.16	55.5	10.34	0.06	>0.05
Duration of Acceleration (msecs)	0 - 1	144.7	192.7	48	0.89	>0.05
	1 - 2	233.7	181	-52.67	0.97	>0.05
Time to peak velocity (msecs)	0 - 1	141.8	217.8	75.94	1.46	>0.05
	1 - 2	233.7	201.9	-31.77	0.61	>0.05
Skewness	0 - 1	0.34	0.25	-0.09	1.40	>0.05
	1 - 2	0.27	0.25	-0.02	0.35	>0.05

Table 3.9 Results from two-way ANOVA for the comparison between vergence-accommodation (disparity OFF) and blur dis-accommodation.
All response parameters are statistically similar between the two responses.

3.5.5.2 Disparity vergence vs. Accommodation

Figures 3.21 and 3.22 show the comparison of the temporal parameters between disparity vergence, vergence-accommodation and blur accommodation. Disparity vergence responses associated with vergence-accommodation are compared with similar response parameters from blur-accommodation and vergence-accommodation. Comparisons were done using a two-way ANOVA. The results are shown separately for

disparity ON **(Figure 3.21)** and disparity OFF **(Figure 3.22)** paradigms. All temporal parameters of the disparity vergence response were found to be similar when compared to vergence-accommodation and blur accommodation. These results applied during both disparity ON and disparity OFF paradigms.

Although most of the temporal parameters could be compared between vergence and accommodation, peak velocity and peak acceleration were represented in different units for the two systems. Accommodative peak velocity was expressed in dioptres (D/s) and vergence velocity was expressed in degrees/s. In order to represent both these systems in comparable units the vergence velocity measures were converted from degrees to meter angles. This allowed both accommodation and vergence to be represented in similar units as the reciprocal of fixation distance in meters. For an average inter pupillary distance of 6.4 cm (for the current study) the conversion factor for 1 degree was calculated to be equal to 0.298 MA. When this conversion was applied to the mean (and SD) values of vergence peak velocity and peak acceleration (**Table 3.4** combined across all amplitudes) it was found that vergence velocity, acceleration during disparity ON and disparity OFF paradigm were 5.19±3.2 MA/s, 87.98 MA/s^2 and 6.53±2.86 MA/s, 166.96±153.32 MA/s^2 respectively. When compared with similar measures on vergence-accommodation and blur-accommodation (combined across all amplitudes), the results showed that the overall vergence velocity and acceleration were significantly greater when compared to VA or blur accomodation (Disparity ON: peak velocity $F_{(2,24)}$=6.078, p=0.007; peak acceleration $F_{(2,24)}$=6.459, p=0.005, Disparity OFF: peak velocity $F_{(2,24)}$=5.491, p=0.019; peak acceleration $F_{(2,24)}$=11.2, p=0.0004).
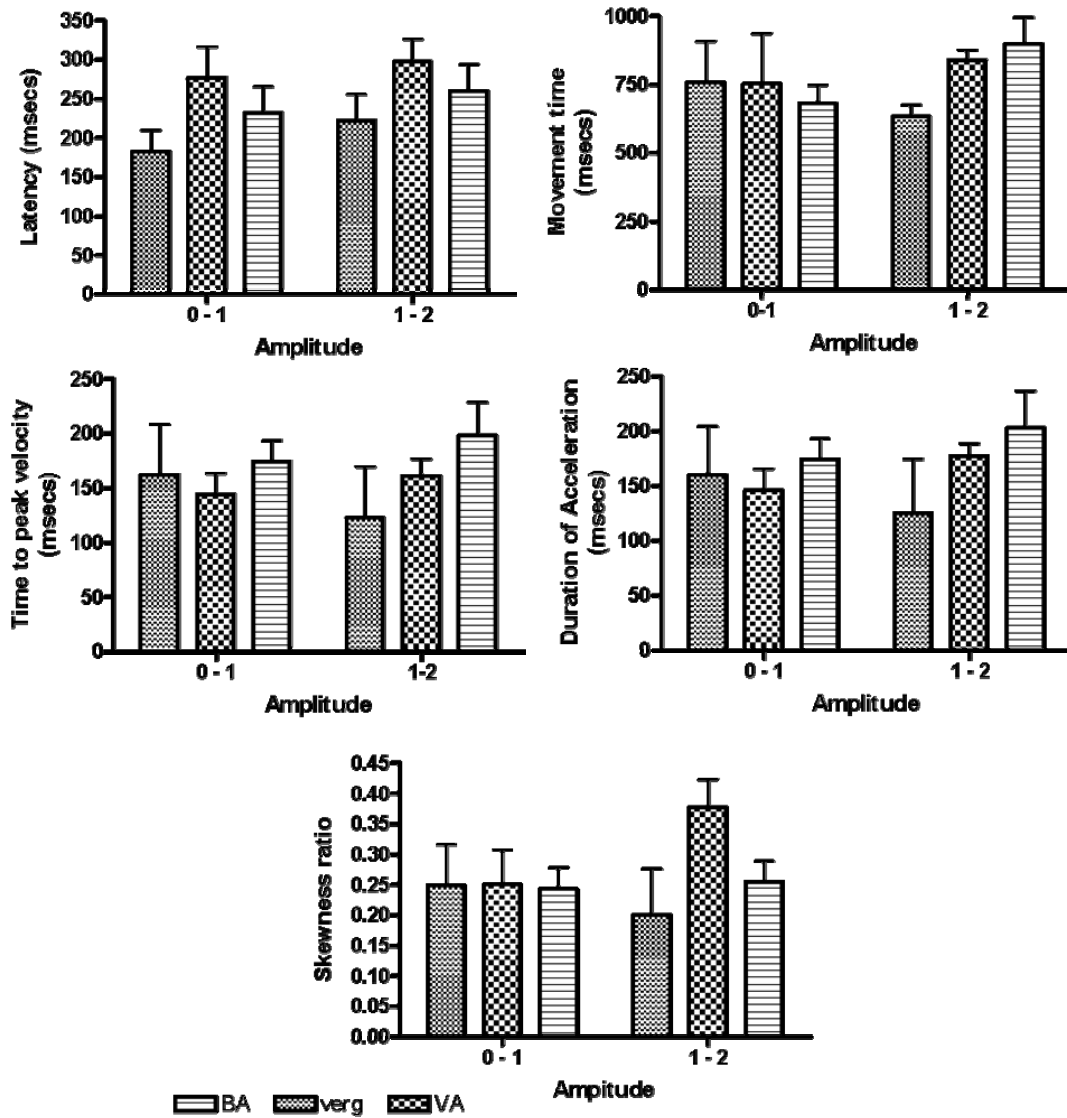
Figure 3.21 Comparison of temporal parameters between vergence, vergence-accommodation and blur accommodation during disparity ON paradigm.
(Mean±SEM). All parameters were similar between vergence, VA and blur accommodation (two-way ANOVA, p>0.05)
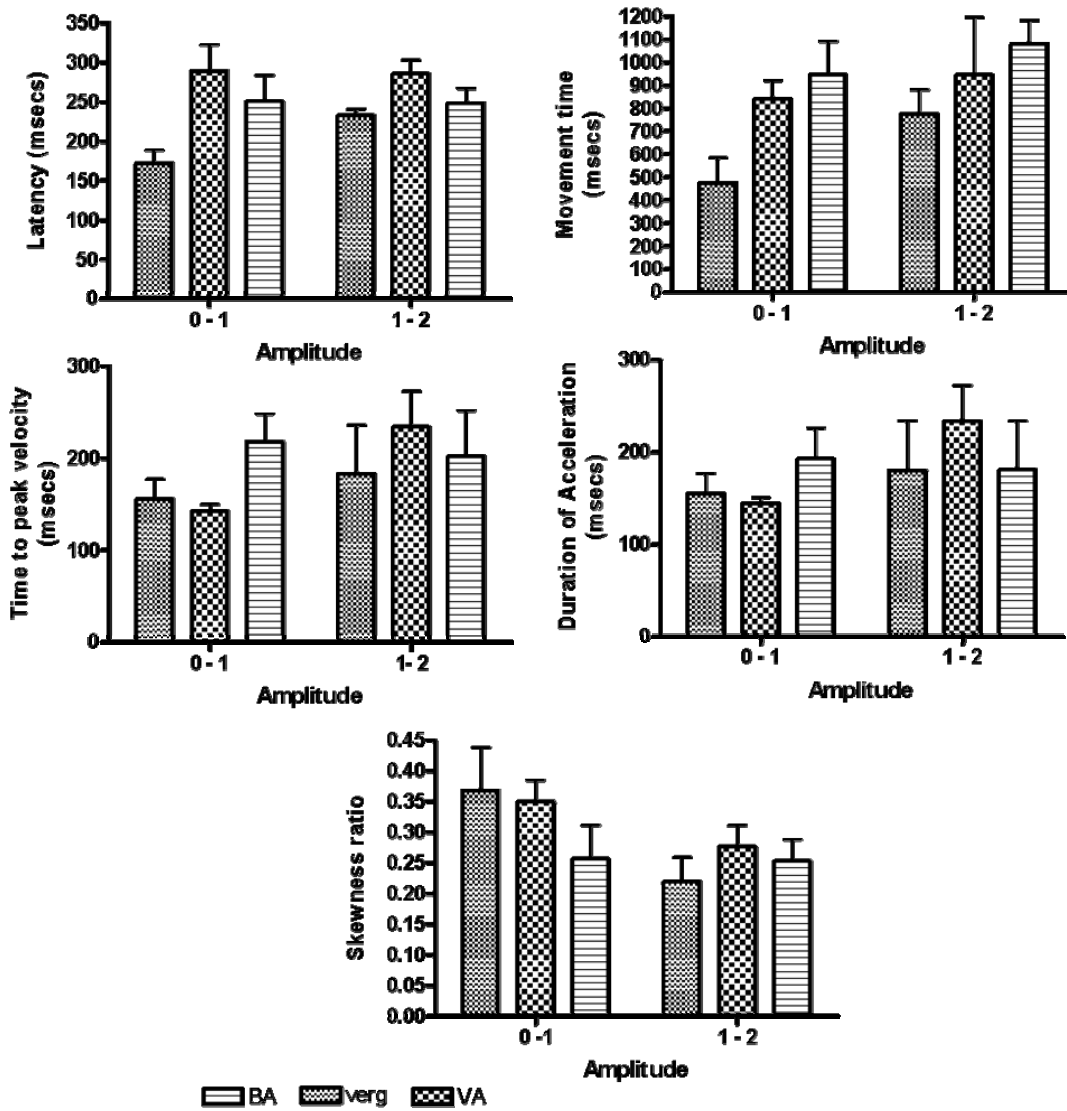
Figure 3.22 Comparison of temporal parameters between vergence, vergence-accommodation and blur dis-accommodation during the disparity OFF paradigm.
(Mean±SEM). All parameters were similar between vergence, VA and blur dis-accommodation (two-way ANOVA, p>0.05)

3.6 Discussion

3.6.1 Static and Dynamic aspects of vergence-accommodation

3.6.1.1 Stimulus and Response VA/V ratios

The results of this study have confirmed that the differences between the stimulus and response VA/V ratios were very small and statistically insignificant. This is keeping with a previous finding that vergence responses are very accurate with smaller steady state errors (Ogle, 1954).

3.6.1.2 Dynamics of vergence-accommodation

The results have provided novel information about many of the dynamic properties of vergence-accommodation. VA has received little attention and few investigations have provided information about its dynamic characteristics. This study is the first investigation to provide an assessment of the first order and second order dynamic properties of vergence-accommodation. The temporal parameters of the VA response such as latency and movement time compare well with previous investigations (Krishnan, Shirachi, & Stark, 1977; Heron, Charman, & Schor, 2001b). The results on the main sequence of vergence-accommodation demonstrate that the dynamics of vergence-accommodation is amplitude dependent. The open-loop accommodation responses also appeared to be equally fast between disparity ON and disparity OFF paradigms within the vergence range and starting positions that were tested. These results suggest that dynamic properties of vergence-accommodation may be independent of vergence direction.

3.6.2 Dynamic similarities between vergence-accommodation and blur accommodation

One of the important results of this study was the comparison of open-loop vergence accommodation with monocular blur driven accommodation. The results from this study were that the temporal properties of these two systems are very similar. When response amplitudes are matched, the first order and second order dynamic properties of vergence-accommodation and blur accommodation are very similar. Retinal disparity and blur are two separate sensory signals that induce accommodation through the same mechanical plant (ciliary muscle, crystalline lens and zonules). The results from this study on humans have shown that in spite of differences in the stimuli, the final accommodative response appears to have similar dynamic properties. This empirical finding suggests that vergence-accommodation and blur accommodation may share a common neural pathway having similar neurological correlates or it may simply be that the plant dynamics are the rate limiting step. Interestingly, two independent observations on single cell recordings in monkeys provide evidence for similar neurological control.

The first investigation (Judge & Cumming, 1986) recorded discharge rates of 110 near response cells (neurons dorsal and dorsolateral to the third nerve nucleus) of 2 monkeys while it tracked targets under different stimulus conditions (blur cues only, binocular with accommodation open-loop, normal viewing). The results of the study showed that, for the majority of the neurons, the amplitude of neuronal discharge rates (modulation) were similar whether the monkey tracked monocularly (blur cues only), binocularly with accommodation open-loop (disparity cue alone) or in normal binocular viewing.

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A second investigation (Zhang, Mays, & Gamlin, 1992) also confirmed this result by showing the activity of the near response cells were similar during monocular accommodation and binocular conflict viewing (accommodation open-loop). The results of this study also suggested that the near response cells could be modelled within the dual interactive feed-back model of accommodation and vergence where cells would receive both direct and cross-link inputs but the relative strengths of these inputs would vary as a function of different gain elements. The innervational strength of the vergence-accommodation cross-link would be represented as the average of these gain elements whose magnitude would be similar to the average gain of a direct input to accommodation (blur).

Thus, the results of both these investigations strongly suggest that blur and disparity signals may independently induce similar neurological innervation from the motor neurons. Axon projections from the motor neurons relay the signal to the plant and since the crystalline lens is the final mechanical plant for both vergence-accommodation and blur accommodation it is possible that the response dynamics of these two systems would also be similar. Alternatively, the two different sensory stimuli (disparity and blur) could induce separate neurological innervations which may combine at an intermediate level providing a similar output in the final common pathway independent of stimulus type. In this case, the similarities in the output in combination with the plant would result in similar empirical responses for the two systems.

3.6.3 Dynamics of disparity vergence

This study investigated the dynamic properties of vergence during the disparity ON/OFF paradigms and the results are similar to previous investigations. The measures of vergence latency, movement time and time to peak velocity agree well with other investigations (Rashbass & Westheimer, 1961; Krishnan, Farazian, & Stark, 1973; Semmlow & Wetzel, 1979; Jones, 1983; Heron, Charman, & Schor, 2001b; Alvarez, Semmlow, & Pedrono, 2005).

Although most of the response parameters of disparity vergence were similar to dynamic measures of accommodation (vergence-accommodation / blur accommodation), peak velocity and peak acceleration of vergence were found to be significantly greater compared to accommodation responses (section 3.5.5.2). These results reflect the differences in the neural pathway and or plant mechanics between accommodation and vergence.

3.6.3.1 Differences between convergence and divergence

The results of the disparity vergence dynamics during disparity ON (convergence) and disparity OFF (divergence) can be compared to the results of Hung et al. (1997). Hung et al. (1997) studied disparity vergence dynamics during symmetrical convergence and divergence (crossed and uncrossed disparity amplitudes of 2, 4, 8, 12 and 16 degrees) and showed that the overall average measures (combined across all stimulus demands) of the dynamic parameters namely latency, time constant, time to peak velocity and total

duration were significantly lower for convergence compared to divergence. Although this was the case for the combined data, there were exceptions to this rule within the individual stimulus demands. The response parameters were not always lower for convergence compared to divergence at all stimulus demands. For example, at lower demands (2 and 4 degrees) time to peak velocity and time constants were not significantly different between convergence and divergence. However, for the same demands latency and total duration of response were significantly lower for convergence compared to divergence. This suggests that the differences in the response parameters between convergence and divergence were inconsistent for smaller stimulus amplitudes. Significant difference was found only when overall results were compared. In the current study, the overall results (combined across all stimulus demands) show that latency, time to peak velocity and response duration were similar between convergence and divergence. The reason for the difference in the overall comparisons between the two investigations can be attributed to differences in the range of stimulus amplitudes studied. While Hung et al. (1997) included a wide range of stimulus amplitudes (2 to 16 degrees) the current study restricted the analysis of vergence to a much smaller range (2 to 5 degrees).

The results from the current study also show that the ratio of the main sequence slopes for convergence and divergence was 1.03, suggesting that the vergence responses were equally fast during both paradigms. This result is lower compared to Hung et al. (1997) who found the ratio to be 2. The reason for this difference can be explained by comparing the methodology between this study and Hung et al. (1997). Hung et al. (1997) created

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crossed and un-crossed disparity demands (convergence and divergence demands) that always changed from a specific baseline position. Hence, the starting position of the responses was always the same for convergence and divergence. In our study, we used a disparity ON / OFF paradigm where a crossed disparity was created from baseline and then the disparity was removed so that the eye could return back to its initial position. Thus, there were no true 'uncrossed disparities'. While the disparity ON stimuli always started from baseline, the disparity OFF stimuli started from different steady state positions during each trial. As the stimulus demands increased, the disparity OFF responses started from closer positions relative to the subject. It has been suggested recently that the peak velocity of divergence eye movements to step changes in stimulus demand, could be strongly influenced by the initial starting position. Divergence movements beginning from positions close to the head were much faster with peak velocities nearly double compared to those beginning at more divergent positions (Alvarez, Semmlow, & Pedrono, 2005). Hence, differences in the initial starting position between disparity ON and OFF in our study could have influenced the results. The vergence responses during the disparity OFF paradigm appear to have become progressively faster with a relatively more proximal starting point. This caused a greater peak velocity in their response making them more equal to the velocity of vergence during the disparity ON paradigm.

3.6.4 Dynamic properties of blur driven accommodation

3.6.4.1 Main sequence relationship

The results from this study on the main sequence of accommodation can be compared with similar measures provided by other investigations. The linear increase in peak velocity with increasing amplitude is consistent with previous observations (Ciuffreda & Kruger, 1988; Kasthurirangan, Vilupuru, & Glasser, 2003; Mordi & Ciuffreda, 2004; Bharadwaj & Schor, 2004). However, slope of the main sequence function is not consistent between the studies ranging from 0.8 to 2.5 for similar aged subjects. What could be the reason for this difference? One of the obvious answers would be the differences in the methods and instruments used in the studies. However, more importantly, there are also differences in the analysis procedure used for the estimation of peak velocity from the raw accommodative position data. Kasthurirangan et al. (2003) used an exponential function to describe the accommodative response and derived their peak velocity mathematically as the first point in the differentiated exponential. This approach suffers from several limitations. The first point on the exponential function would correspond to the onset of the response in the position trace. This would mean that peak velocity occurred at response onset, a situation which is not physiologically possible. The use of the exponential function would also limit the description of the response as a first order approximation and hence acceleration dynamics cannot be determined. On the other hand, in the current study, the peak velocity and peak accelerations were computed from the position trace by using an FFT based procedure. This procedure allowed an estimation of both velocity and acceleration with a high signal to noise ratio (Appendix 1). An estimation of the higher order parameters was made

possible in this study because of a newer technology (high speed photorefraction) that allowed for assessment of accommodation responses at a much higher sampling rate. The results show that peak velocity occurs in the first $1/3^{rd}$ of the response amplitude and is similar for both accommodation and dis-accommodation. Another important factor is the range of accommodative stimuli used between the investigations. The maximum amplitude of the response accommodation is found to be different between investigations because of the differences in the range of stimulus demands. When responses are studied over a larger range, the relationship between amplitude and peak velocity tend to become more non-linear. On the other hand, linear regression functions are used when a smaller range of amplitudes are studied. Hence, main sequence slope comparisons between studies should be viewed with caution.

The results of the current study have also provided results on dis-accommodation. The study results have shown that dis-accommodation and accommodation have similar velocities for the range of stimulus demands tested. In our study, dis-accommodation responses always ended at the same final position and their amplitude vs peak velocity plot was linear and less variable between the subjects. Previous investigations in monkeys (Vilupuru and Glasser, 2002) and humans (Kasthurirangan & Glasser, 2003) have also suggested position dependent dis-accommodation dynamics that were less variable between subjects and our results from this investigation concur with their findings.

3.6.4.2 First order and second order dynamics

This study has also provided important information relating to both the first order and second order dynamics of accommodation and dis-accommodation. The velocity and acceleration of the response was similar for accommodation and dis-accommodation. Since the range of accommodative stimuli included in this study is limited it does not allow the interpretation on how the peak velocity was reached during a typical accommodation and dis-accommodation response. However, this was not the primary intent of this investigation. This study fundamentally aimed at comparing dynamics of vergence-accommodation with similar measures of monocular blur driven accommodation. Since vergence-accommodation responses are seldom greater in magnitude, the examination of blur-accommodation and its dynamics were intentionally limited to a smaller range of amplitudes in order to match with the responses of vergence-accommodation. The results of this investigation on the higher order properties of accommodation simply suggest that accommodation and dis-accommodation tend to have similar dynamic properties at lower response amplitudes. However, as shown in this study and previous investigations, the dynamic properties of accommodation and dis-accommodation change individually as a function of their response amplitude and hence the differences between the two responses can only be better estimated when response parameters are studied over a wide range of amplitudes.

4 General Discussion and Conclusion

Accommodation and vergence are two interacting ocular motor systems that help provide clear single binocular vision. Cross-link interactions, AV and VA have been recognised for their role in regulating the responses of the two systems. Knowledge of the dynamic properties of VA is essential to understand the relative contribution of this parameter towards the net accommodative response under binocular viewing conditions where both blur and disparity signals are operating. While accommodation is driven as a reflex by retinal blur, VA reflects the change in accommodative response driven when retinal disparity alone is present as the signal. Thus binocular vergence-accommodation and monocular blur driven accommodation have different sensory stimuli but the motor responses drive the same mechanical plant (crystalline lens). Hence, comparison of VA and blur accommodation dynamics would help outline the effect of two completely different sensory stimuli on response accommodation. The investigations described in this thesis have attempted to provide a more detailed analysis of this cross-link.

The initial study (chapter 2) investigated the first order dynamics of VA and blur accommodation using a commercially available photorefractor (PowerRefractor). The results showed that the dynamics of vergence accommodation were amplitude dependent, with peak velocity of VA increasing linearly over the range of response magnitudes studied. Also, when VA amplitudes were matched between disparity ON and disparity OFF, the rate of change of peak velocity (slope) was found to be lower during disparity

ON (convergence) compared to disparity OFF (divergence). However, the analysis method (cubic polynomial interpolation) did not fit the higher amplitude VA responses well during the disparity ON paradigm causing peak velocities at higher amplitudes to be under-estimated. Also, disparity vergence was assumed as a stimulus measure and it was not possible to confirm if the differences in vergence-accommodation between the two paradigms were related to the differences in the dynamic responses of disparity convergence and divergence. Hence it could not be shown if the difference found between VA responses during disparity ON and disparity OFF was a true effect. Furthermore, a complete assessment of the similarities / differences between the responses of vergence-accommodation and blur accommodation could not be attempted because only peak velocity was measured and information about other temporal parameters was not known.

Accordingly, to address these limitations and provide a more comprehensive assessment of VA, a second study (chapter 3) was designed and accommodation and vergence responses were simultaneously studied and their response dynamics were compared. This was made possible by the development of new instrumentation that allowed for high speed measures of accommodation through a custom designed digital photorefractor and its synchronization with a modified disparity stimulus generator / stereo eye tracker. The instrumentation allowed for both first order and second order properties (chapter 3) of vergence-accommodation to be studied and the responses to be compared with similar measures of accommodation driven by blur. The results showed that both these response have similar dynamic properties. The VA measures were also studied as a function of

convergence and divergence and their response dynamics were shown to be similar between the two conditions within the stimulus range studied.

From the results of the two studies, several important issues remain to be discussed. These questions relate to the empirical and instrumentation aspects of the two investigations. These questions will be addressed throughout the rest of this discussion.

4.1 Empirical results

4.1.1 Retinal Disparity – a strong enough cue for accommodation?

Under normal viewing conditions, accommodation and vergence are tightly coupled with blur and disparity signals input to the two systems as negative feedback. The net accommodative response under binocular viewing conditions is a cumulative output of blur accommodation and vergence-accommodation crosslink. However, the relative weight of the contribution of blur and vergence accommodation in normal viewing is yet to be ascertained. When disparity alone is presented as a cue in the absence of blur, vergence-accommodation is induced and the results from this investigation have shown that vergence-accommodation has a good dynamic response with temporal characteristics that are very similar to monocular blur driven accommodation. This result emphasizes that retinal disparity presented as an independent signal is capable of driving accommodation in a manner similar to blur. It is perhaps not surprising that Fincham and Walton (1957) found VA to be of sufficient magnitude in young adults to allow focus of near objects.

4.1.2 Dynamics of vergence-accommodation during convergence and divergence

While convergence is known to cause an increase in accommodation via the VA cross-link, divergence would be expected to cause a decrease in VA. However, does VA change at the same rate between convergence and divergence? This question was asked during the introduction of this thesis. Disparity driven convergence and divergence have been suggested to have different dynamic properties and it would be interesting to know if the differences between them would influence vergence-accommodation. The results of the investigations described in this thesis have made an attempt to answer this question.

When vergence-accommodation was first measured as a disparity ON/OFF paradigm using the PowerRefractor, significant differences were found in the slope of the amplitude vs. peak velocity relationships between vergence-accommodation during disparity ON and disparity OFF (**Figure 2.3**). Specifically the slope of the linear regression describing the main sequence was relatively flat during disparity ON compared to disparity OFF. However, this result could not be confirmed as a true effect for two reasons. Although it was discussed that one of the main reasons for this difference could be due to an under-estimation of the peak velocities by the cubic polynomial interpolation, the possibility of differences existing at the level of disparity vergence had to be ruled out (section 2.6.4.1). Accordingly in Chapter 3, this result was clarified. When vergence-accommodation was coupled with disparity vergence measures, it was clear that the dynamics of vergence-accommodation were similar between disparity ON (convergence) and disparity OFF (divergence). Peak velocity and all

temporal parameters of vergence-accommodation were similar during convergence and divergence. These results show that, for the range of stimulus amplitudes studied, the dynamics of vergence-accommodation appear to be independent of vergence type. This result has also shown that the reason for finding differences in chapter 2 could be related to the under-estimations of the cubic polynomial interpolations. When the analysis technique was improved in Chapter 3 by using an FFT based technique, vergence-accommodation velocity showed no difference when compared between disparity ON and disparity OFF. This suggests that, for the range of stimulus demands studied, no true differences were found between VA during disparity ON and disparity OFF.

4.1.3 Are the dynamics of vergence-accommodation better than blur accommodation?

From the results of the current investigation, vergence-accommodation and blur accommodation were found to have similar dynamics properties. The responses were equally fast and their temporal parameters very similar. Although this may be the case in humans, an earlier study on monkeys has suggested that the dynamics of vergence-accommodation may be *'superior'* to blur-accommodation (Cumming & Judge, 1986). The study specifically reported that accommodation open-loop (AOL) viewing resulted in smaller phase lags to sinusoidal stimuli compared to monocular blur driven accommodation (Cumming & Judge, 1986). A careful examination of their data revealed that the difference between the two paradigms were not apparent at all frequencies and showed significant variation between the two monkeys tested. Furthermore, the actual gain values between AOL viewing and monocular accommodation were very similar.

These results do not provide strong evidence for the claim that the dynamics of vergence-accommodation may be superior when compared to that of blur.

On the other hand, the investigations described in this thesis revealed that the temporal parameters in humans were not consistently different in the two systems for the range of stimulus amplitudes tested. Future work is necessary to ascertain if differences exist at higher amplitude levels beyond the range studied in this report and to examine the effect of starting position.

4.1.4 Dynamics of blur driven accommodation and dis-accommodation: current concepts and future directions

Blur accommodation dynamics have been well studied in the literature and many of its dynamic characteristics are known. Recent investigations suggest that the velocity and acceleration characteristics of accommodation may be independently controlled (Kasthurirangan, Vilupuru, & Glasser, 2003; Mordi & Ciuffreda, 2004; Bharadwaj & Schor, 2004). Furthermore, accommodation and dis-accommodation have been suggested to adopt different control strategies to reach the final response or steady state (Bharadwaj & Schor, 2004; Bharadwaj, Kim, & Schor, 2005). However, most of these study results are based on young subjects with normal amplitudes of accommodation with stimuli that are within the linear range of the stimulus-response curve of accommodation. With presbyopia, this linear range decreases (Hamasaki, Ong, & Marg, 1956) and hence effects of non-linearities at higher stimulus levels will be prominent. Further work is needed to sort out the differences between the two systems and how their dynamics are relatively

affected during the course of presbyopia. The bio-mechanical, optical and physical properties of the crystalline lens have been known to change with age (Glasser & Campbell, 1999) and the plant mechanics have been suggested to be the rate limiting step for accommodation and dis-accommodation response dynamics (Kasthurirangan, Vilupuru, & Glasser, 2003). Future work should be aimed at comparatively studying lens changes in relation to response dynamics of accommodation and dis-accommodation. This will help understand the effect of the physiological changes in the crystalline lens (plant) properties on the empirical accommodation / dis-accommodation responses.

Recent investigations on accommodation dynamics have suggested that peak acceleration of blur accommodation to be independent of response magnitude (Bharadwaj & Schor, 2004). The authors also claimed that accommodation is not the only ocular motor system to exhibit this relationship and that saccades have similar acceleration characteristics. However, studies on velocity and acceleration characteristics of saccades have shown that peak velocity and peak acceleration of saccades increased for response amplitudes up to 40 degrees and saturate at higher amplitudes (Collewijn, Erkelens, & Steinman, 1988). Therefore the independent acceleration properties of accommodation found by Bharadwaj and Schor (2005) may be unique for the accommodation system or may not be clearly seen in their study because of a smaller range of stimulus amplitudes (up to 4D). Future work should be aimed at investigating the response parameters over a larger range of response amplitudes to obtain a complete understanding.

4.2 Instrumentation

One of the major improvements in the data acquisition process was the development of the high speed photorefractor. The new photorefractor allowed for high speed measures of accommodation thereby providing a better resolution of accommodative position. As discussed earlier in **section 2.6.4.3**, the advantages of high speed photorefraction allowed a more accurate assessment of first order and second order accommodation dynamics.

In addition to sampling rate, another important factor is the choice of analysis routine that is used for the estimation of the temporal parameters (example response onset, response end). For the investigation described in this thesis, an FFT algorithm was used to smooth the response position (first order and second order differentials). The cut off frequency of this algorithm was set to 10 Hz such that a high signal to noise ratio could be maintained (Appendix 1). This was important because differentiation may introduce noise and it is important to ensure that a smoothing operation removes only the noise frequencies and maintains the signal frequencies present in the response. The FFT smoothing allowed a high signal to noise ratio thus maintaining the signal frequencies in the response (Appendix 1). With a good smoothing routine in place, a velocity threshold criterion could be used to objectively determine the temporal parameters (response start, response end, latency, movement time etc.) thereby avoiding subjective bias.

Some of the previous investigations (Vilupuru & Glasser, 2002;Kasthurirangan, Vilupuru, & Glasser, 2003) have used the PowerRefractor (sampling at 25Hz) to measure accommodative response and fitted the response using exponential functions

which preclude the measurement of higher order dynamics. The exponential fit starts abruptly and predicts that the accommodative response starts off with maximum velocity – a situation that is not physiologically possible. On the other hand, the FFT based procedure used in this study qualitatively described the response position as a smooth increase / decrease and it also allowed an accurate estimation of velocity and acceleration dynamics. The FFT procedure also predicted the appropriate onset of peak velocity at the first $1/3^{rd}$ of the total response duration.

4.2.1 Future of high speed photorefraction

Eccentric photorefraction has always been considered a useful tool for the measurement of accommodation. Its remote working distance, simplicity of the procedure and open field design are particularly suited for testing young infants and children. With improvement in technology as a high speed device, and a reliable estimation of response dynamics, high speed photorefraction appears to have great potential for future investigations involving dynamic measurement of accommodation in children and adults.

Future research would be aimed at investigating the dynamics of accommodation at various stimulus amplitudes and different age groups. The current study limited the analysis of the accommodation dynamics to lower stimulus levels that were within the linear range of the stimulus-response function of accommodation. The stimulus amplitudes were deliberately kept lower in order to match with measures of vergence-accommodation. However, in order to obtain a fuller understanding of the blur accommodation dynamics, it is necessary to study the change in these temporal

parameters over a wider range of stimulus amplitudes. This would help in the understanding the fundamental characteristics of accommodation and outline differences in the response dynamics when stimuli are within both the linear and non-linear range of the stimulus-response function.

The high speed photorefractor described still has room for improvement. Although the technique of photorefraction described in this thesis resulted in a high speed output, the analysis of the individual images was all done manually. This procedure was very time consuming. Future work could be directed at automating the analysis routines and developing an independent analysis algorithm which would ideally analyze all the frames from the raw video file using a fully automated procedure and output the accommodative response.

4.3 Conclusion

This thesis has provided a more detailed analysis of the dynamic properties of vergence-accommodation cross-link. The empirical results described in this thesis have clearly demonstrated the importance of retinal disparity in the dynamic control of accommodation. Even if disparity is presented as an independent signal it is capable of driving accommodation similar to that of blur. The dynamic similarities between vergence-accommodation and blur-accommodation strongly suggest a common neural pathway controlling the two systems. With proper understanding of the cross-link interactions between vergence and accommodation, it is possible to outline the specific the contribution of these individual components during normal binocular vision.

5 Appendix 1

5.1.1 Analysis of the temporal parameters of accommodation response

In order to analyze the accommodative responses obtained from the photorefractor and the vergence response obtained from the stereo eye-tracker, an analysis procedure was developed that would allow for the estimation of the various temporal parameters in both these responses. The main aim of this procedure was to allow for an accurate estimation of the temporal parameters in the response by reducing the effect of noise that would be normally present in the raw position / differentiated velocity trace. The following section describes the analysis procedure used in the study and its comparison between a 1D response and a 0D response. For the sake of simplicity and to avoid repetition, the analysis procedure has been explained for accommodative responses only. The same procedure was applied to the vergence responses.

5.1.2 Analysis procedure

For each subject and each stimulus the raw position data of accommodation obtained from the photorefractor was averaged across the trials and plotted as a function of time. An example of an averaged accommodative position response to a 1D and a 0D stimulus demand is shown in **Figure 5.1A**. The averaged position data was then smoothed with a 5pt FFT smoothing function. The FFT smoothing routine smoothed the position data based on the formula,

$F = 1 / n * \Delta t$

Where, n is the number of points (in this case n =5) and Δt was the sampling interval. For measures from the photorefractor at a sampling rate of 75Hz, Δt was equal to 0.0133.

Substitution of these variables resulted in a cut-off frequency of 15Hz. Thus, the FFT smoothing routine removed frequencies higher than 15Hz in our position data resulting in a smoother response as seen **Figure 5.1B**. The raw position data was also differentiated using a two point differentiator and subsequently smoothed using the FFT smoothing routine. The smoothed velocity and acceleration profiles are shown in **Figures 5.1C and 5.1D**.

A velocity threshold criterion was applied to the smoothed position response to identify the start and end co-ordinates. The start of the response was computed by identifying the first point where the slope exceeded 0.5D/s, continued to do so for the next 100 msecs (8 consecutive samples) and also changed in the correct direction. A similar and inverse criterion was applied to find the end co-ordinates of the response. These start and end co-ordinates were also verified by eye to ensure accuracy. From the start and end coordinates of the response, the amplitude of the response and its movement time were computed. Amplitude was defined as the absolute difference in the accommodative response (Y) between the start and end co-ordinates while movement time was defined as the difference in time (X) between the start and end co-ordinates. Peak velocity was identified as the maximum velocity in the differentiated smoothed curve. At the time when peak velocity occurred, the magnitude of velocity in the 0D response (0.027) was significantly lower than the peak velocity for the 1D response (3.81). A similar effect was noted for acceleration as well. At the time of peak acceleration, the magnitude of the acceleration was $31.57D/s^2$ for the 1D response compared to $5.76D/s^2$ for the 0D response.

5.1.3   Signal to Noise ratio

The dynamic signal to noise ratio was also computed and compared across the two levels of accommodation. The procedure for calculating the dynamic SNR was adopted from an earlier report on accommodation dynamics that provided similar SNR ratios for the acceleration measures (Bharadwaj & Schor, 2004). First, the root mean square (RMS) noise was computed for the two accommodative levels from their respective velocity traces. The RMS was calculated for duration of 300 msecs following the end of the response. The differentiated and smoothed velocity profile was then divided by the RMS value to provide the dynamic signal to noise ratio for each accommodative level (0D and 1D).

The RMS noise was found to be 0.23D/sec for the 1D response and 0.15D/sec for the 0D response. The dynamic signal to noise ratio for the two levels of accommodation is shown in **Figure 5.2**. At the time when peak velocity occurred, the signal to noise ratio for the 1D response was very high (15:1). This result confirmed that the velocity responses could be measured reliably using the smoothing routine.
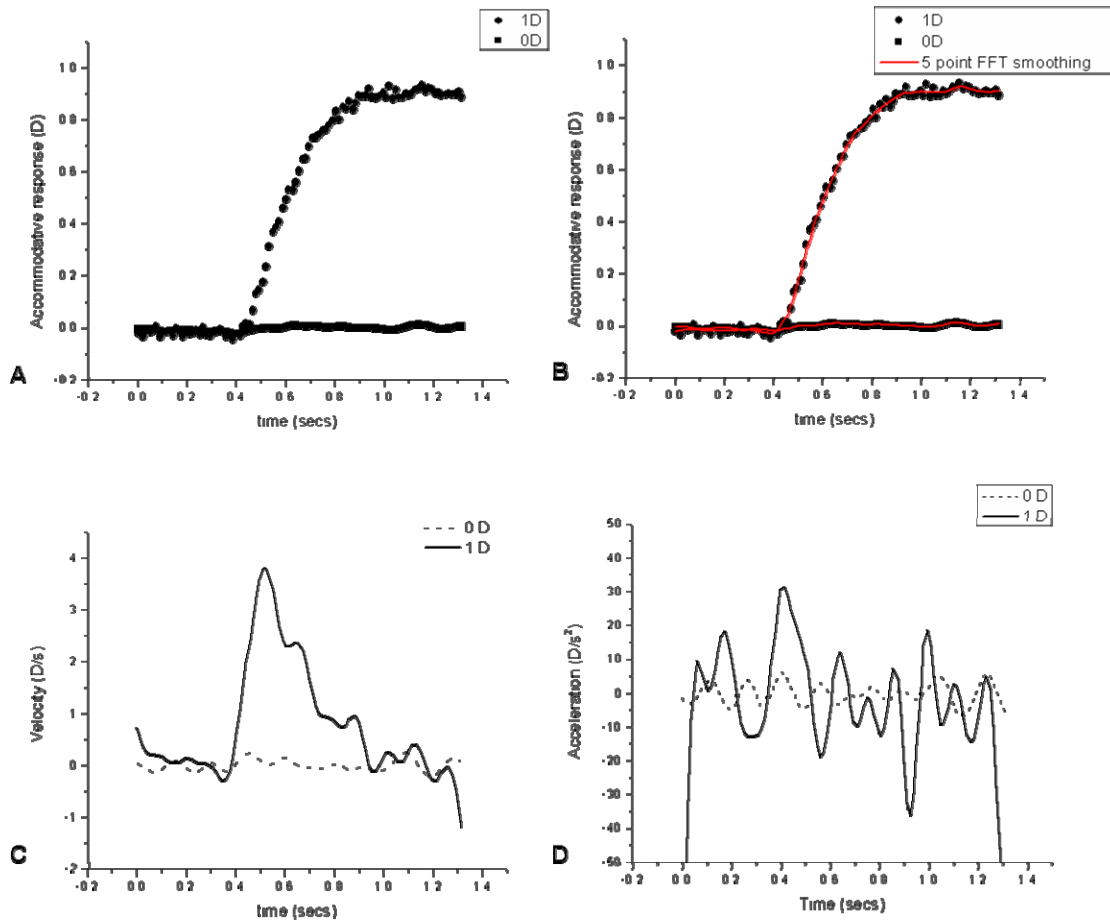
Figure 5.1 Estimation of temporal parameters from the response.
A. The raw position trace for 0D and 1D. The 1D response shows a positive change with stimulus (signal and noise) while the 0D represents fluctuations in the response position in the absence of a signal (noise). B. FFT smoothing of the two responses (solid line). The smoothed responses were used in the computation of start and end co-ordinates, response amplitude and movement time. C. Smoothed velocity profiles for 0D (dashed line) and 1D (solid line). The raw position data was first differentiated and smoothed using the FFT procedure. Peak velocity during 1D (signal and noise) is much greater compared to 0D (noise). D. Smoothed acceleration profiles for 0D and 1D responses. At the time when peak acceleration occurred, value at 1D was significantly greater compared to 0D.

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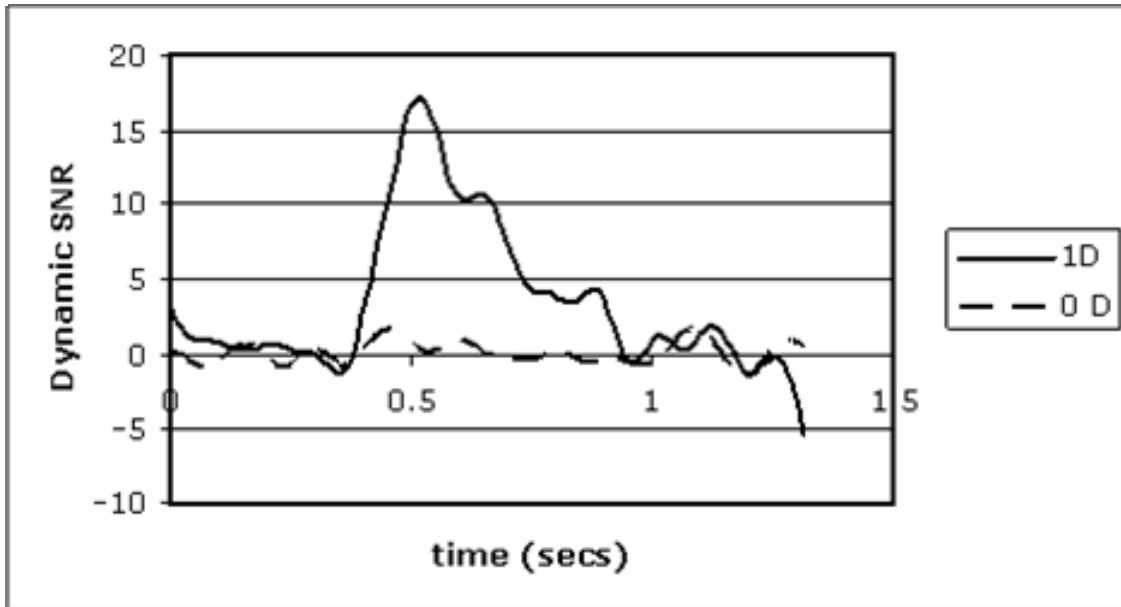
Figure 5.2 The dynamic signal to noise ratios for two accommodative levels (0D and 1D)
The 0D response is shown as a dotted line and the 1D response is shown as a solid line. Note the high SNR
at the time when peak velocity occurred.

6   Appendix 2

6.1   Improvements in the DSG Interface

The DSG was modified so that images and gratings could also be presented as disparity targets on the stereo monitor. A screen shot of the improved DSG interface is shown in **Figure** 6.1. The newer interface allowed the gratings/bitmaps to be initialized so that they could be presented in stereo monitor.

Figure 6.1 Screen shot of the stereo file (SDS file).
The SDS file basically consists of a set of instructions arranged as a sequence. The second and third columns (from the left) denote the disparity demand that is presented to the right and left eye respectively (denoted in the figure by the small arrows). A zero value indicates that there is no disparity in the image and it will be projected in the center of the screen. A negative value indicates crossed retinal disparity and a positive value indicates an uncrossed retinal disparity. The last two columns (denoted by the large arrows) represent the image file that will be presented to the right and left eye. In this case, it is a 0.2cpd difference of Gaussian target (gauss2c.bmp). The target is presented as an asymmetrical vergence paradigm with all the crossed disparity projected to the right eye and no disparity for the left eye.

6.2   Appendix 3

6.3   Calibration results of the PowerRefractor

Figure 7.1 shows a plot of the induced refractive error (X) vs. measured refractive error (Y) for the six subjects. The pooled slope (across all subjects) was 0.99 (R^2 value = 0.99, p <0.0001). The 95% confidence intervals for the slope ranged from 0.97 to 1.01.
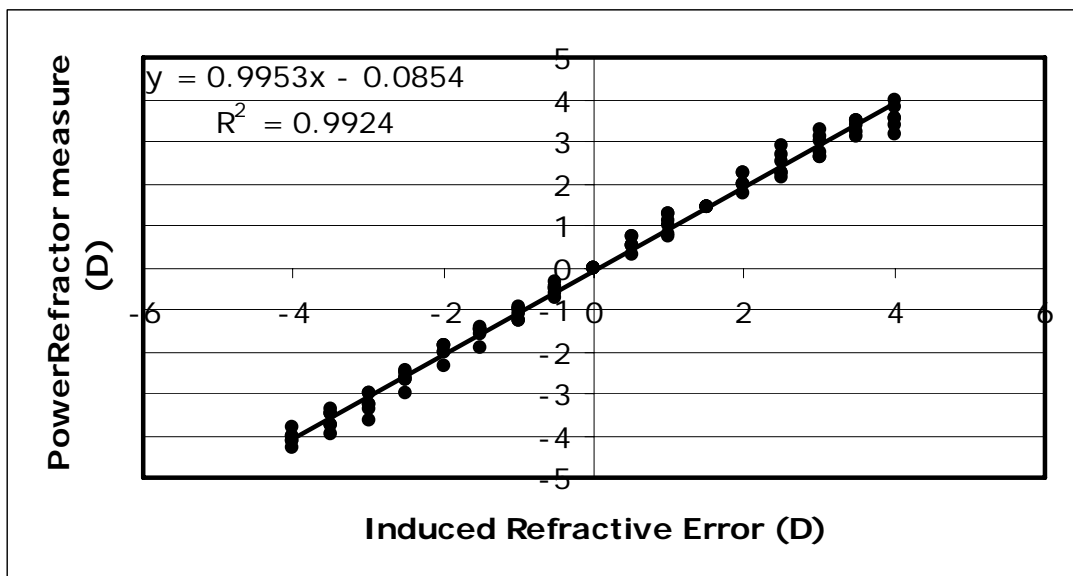
Figure 6.2 Plot of the PowerRefractor calibration showing data from all six subjects.
The calibration function was not significantly different from a 1:1 line.

The calibration study showed that there was a linear change in the refractive state of the eye (as recorded by the PowerRefractor) with increasing induced refractive error. There was no significant difference between the PowerRefractor calibration and a 1:1 relationship for a working range of ±4D. Since vergence-accommodation measures are usually well within this amplitude, the calibration of the PowerRefractor could be used without the need for any adjustments.

6.4 Calibration of the PowerRefractor with LCS goggles

The calibration of the PowerRefractor was repeated on 1 subject (SU) through the LCS goggles. The results are shown in **Figure** 7.2. The presence of the LCS goggle did not affect the PowerRefractor measures.
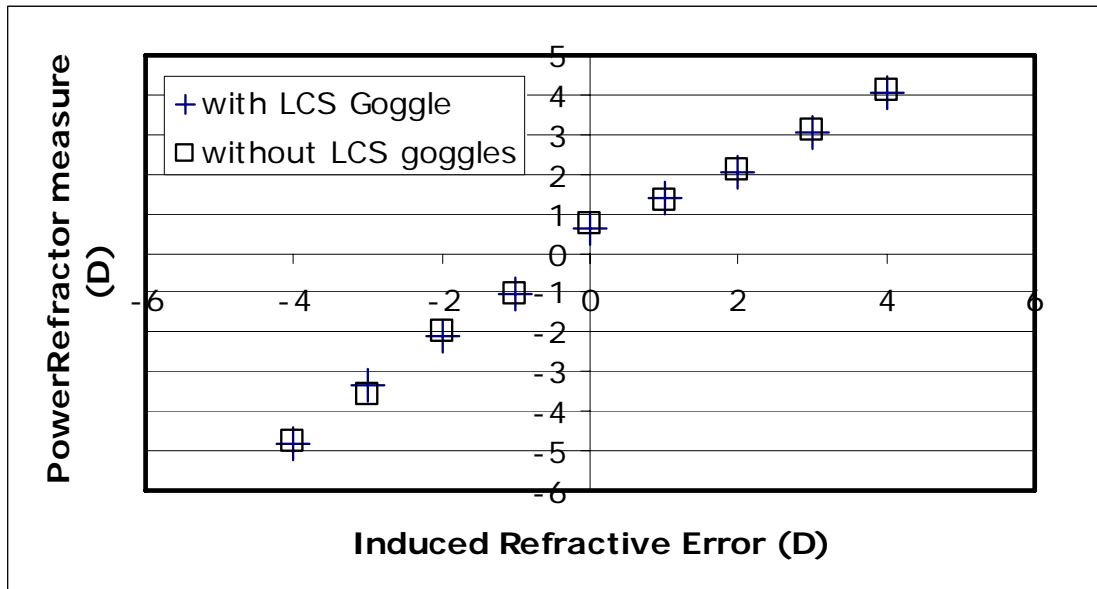
Figure 6.3 Calibration of the PowerRefractor with and without the LCS goggles.
The slope of the calibration function was similar during both paradigms (slope with LCS goggles= 1.08, without goggles = 1.09).

7 Appendix 4

7.1 Codes for the analysis of photorefraction brightness profiles

7.1.1 AutoPro (ImagePro Plus, Media Cybernetics, USA) codes

Sub profile()

```
'F8
'Created by Jason P Meyers and Rajaraman Suryakumar
'Sets DDE options to row 1, column 1 and then take the line profile of 256 frames, of sequence file, at one
time. The line profiles of every frame are then exported into adjacent columns of an active excel worksheet.
Dim i As Integer
        ret = IpDde(DDE_SET, "row", "1")
        ret = IpDde(DDE_SET, "col", "1")
For i = 1 To 250
        ret = IpProfSave("", S_DDE)
        ret = IpSeqPlay(SEQ_NEXT)
Next i
ret = IpDde(DDE_SET, "row", "50")
        ret = IpDde(DDE_SET, "col", "1")
        ret = IpDde(DDE_SET, "target", "E:\Program Files\Microsoft Office\Office10\EXCEL.EXE")
For i = 1 To 110
        ret = IpProfSave("", S_DDE)
        ret = IpSeqPlay(SEQ_NEXT)
Next i
End Sub
```

Sub Whole_sequence_Profile()

'F12

'Created by Jason Meyers

'Used when whole sequence file can be captured at the same time. This will set the DDE options to row 1, column1 and then take the line profile of 5250 frames of the sequence file. These line profiles are exported into adjacent columns in excel worksheet. And after every 250 line profiles the DDE options are changed to export profiles into excel 50 rows down and beginning in column 1 again. Since there is a maximum of 256 columns in excel and there are 5250 frames in sequence files that are exported to excel

Dim i As Integer

    ret = IpDde(DDE_SET, "row", "1")

    ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

    ret = IpProfSave("", S_DDE)

    ret = IpSeqPlay(SEQ_NEXT)

Next i

    ret = IpDde(DDE_SET, "row", "50")

    ret = IpDde(DDE_SET, "col", "1")

    ret = IpDde(DDE_SET, "target", "E:\Program Files\Microsoft Office\Office10\EXCEL.EXE")

For i = 1 To 250

    ret = IpProfSave("", S_DDE)

    ret = IpSeqPlay(SEQ_NEXT)

Next i

    ret = IpDde(DDE_SET, "row", "100")

    ret = IpDde(DDE_SET, "col", "1")

    ret = IpDde(DDE_SET, "target", "E:\Program Files\Microsoft Office\Office10\EXCEL.EXE")

For i = 1 To 250

    ret = IpProfSave("", S_DDE)

    ret = IpSeqPlay(SEQ_NEXT)

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```
Next i

        ret = IpDde(DDE_SET, "row", "150")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "200")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "250")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "300")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "350")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250
```

```
        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "400")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "450")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "500")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "550")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "600")
```

```
        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "650")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "700")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "750")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "800")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)
```

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```
Next i

        ret = IpDde(DDE_SET, "row", "850")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "900")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "950")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "1000")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "1050")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250
```

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```
        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "1100")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

        ret = IpDde(DDE_SET, "row", "1150")

        ret = IpDde(DDE_SET, "col", "1")

For i = 1 To 250

        ret = IpProfSave("", S_DDE)

        ret = IpSeqPlay(SEQ_NEXT)

Next i

End Sub
```

7.1.2   MS Excel macros

```
' SLOPE Macro

' Macro recorded 30/06/2004 by Jason P Meyers

'Calculates the line profile slopes of 250 frames of the seq files, then transposes the values bellow

' Keyboard Shortcut: Ctrl+s

'

  Selection.EntireColumn.Insert

  Range("A1").Select

  ActiveCell.FormulaR1C1 = "1"

  Range("A2").Select

  ActiveCell.FormulaR1C1 = "=1+R[-1]C"
```

Range("A2").Select

Selection.AutoFill Destination:=Range("A2:A45"), Type:=xlFillDefault

Range("A2:A45").Select

ActiveWindow.SmallScroll Down:=12

Range("A47").Select

ActiveCell.FormulaR1C1 = "slope"

Range("A96").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("B47").Select

ActiveCell.FormulaR1C1 = "=SLOPE(R[-46]C:R[-2]C,R1C1:R45C1)"

ActiveWindow.SmallScroll Down:=6

Range("B47").Select

Selection.AutoFill Destination:=Range("B47:IP47"), Type:=xlFillDefault

Range("B47:DF47").Select

Selection.Copy

Range("B96").Select

ActiveSheet.Paste

Range("A47").Select

Range("A47:IP47").Select

Selection.Copy

Sheets("Sheet2").Select

Range("A1").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

Range("B96:DF96").Select

Selection.Copy

```vbnet
    Sheets("Sheet2").Select

    ActiveCell.Select

    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

        :=False, Transpose:=True

    ActiveCell.Offset(250, 0).Range("A1").Select

    Range("C1").Select

    ActiveCell.FormulaR1C1 = "Time"

    Range("D1").Select

    ActiveCell.FormulaR1C1 = "Aresp"

End Sub
```

```vbnet
' Cal_equation Macro

' Created by Jason P Meyers

' Calculates the dioptric values of the line profile slope, and records it into column D on sheet 2 of excel file

' Keyboard Shortcut: Ctrl+Shift+D

    Range("D2").Select

    ActiveCell.FormulaR1C1 = "=(RC[-3]* -1.1224)+ 0.747"

    Range("D2").Select

    Selection.AutoFill Destination:=Range("D2:D361"), Type:=xlFillDefault

    Range("D1:D361").Select

End Sub
```

```vbnet
' Everything Macro

' Created by Jason P Meyers

' Performs Slope macro and copies slope values to sheet 2 column A, and then performs Cal equation
macro.

' Keyboard Shortcut: Ctrl+s

    Columns("IV:IV").Select
```

```
    Selection.ClearContents

    Application.Run "PERSONAL.XLS!slope"

    Application.CutCopyMode = False

    Application.Run "PERSONAL.XLS!Cal_equation"

End Sub
```

```
' Whole_Slope Macro
```

' Created by Jason P Meyers

' This macro will calculate the line profile slope of the 5250 frames (whole seq file), and then transpose all the values into sheet 2 column A. As well, this macro will calculate the dioptric values of the line profile slope and record it into column D of sheet 2. And then setup an XY scatter line graph for columns C (seq time) and D (dioptric slope.)

' Keyboard Shortcut: Ctrl+w

'

```
    Columns("A:A").Select

    Selection.Insert Shift:=xlToRight

    Range("A1").Select

    ActiveCell.FormulaR1C1 = "1"

    Range("A2").Select

    ActiveCell.FormulaR1C1 = "=1+R[-1]C"

    Range("A2").Select

    Selection.AutoFill Destination:=Range("A2:A45"), Type:=xlFillDefault

    Range("A1196").Select

    ActiveCell.FormulaR1C1 = "Slope"

    Range("A1146").Select

    ActiveCell.FormulaR1C1 = "Slope"

    Range("A1096").Select

    ActiveCell.FormulaR1C1 = "Slope"
```

```
Range("A1046").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A996").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A946").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A896").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A846").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A796").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A746").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A696").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A645").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A596").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A546").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A495").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A446").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A396").Select

ActiveCell.FormulaR1C1 = "Slope"
```

```
Range("A346").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A296").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A246").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A196").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A146").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A96").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("A47").Select

ActiveCell.FormulaR1C1 = "Slope"

Range("B47").Select

ActiveCell.FormulaR1C1 = "=SLOPE(R[-46]C:R[-2]C,R1C1:R45C1)"

Selection.AutoFill Destination:=Range("B47:IQ47"), Type:=xlFillDefault

Range("B47:IQ47").Select

Selection.Copy

Range("B96").Select

ActiveSheet.Paste

Range("B146").Select

ActiveSheet.Paste

Range("B196").Select

ActiveSheet.Paste

Range("B246").Select

ActiveSheet.Paste

Range("B296").Select
```

```
ActiveSheet.Paste

Range("B346").Select

ActiveSheet.Paste

Range("B396").Select

ActiveSheet.Paste

Range("B446").Select

ActiveSheet.Paste

Range("B495").Select

ActiveSheet.Paste

Range("B546").Select

ActiveSheet.Paste

Range("B596").Select

ActiveSheet.Paste

Range("B645").Select

ActiveSheet.Paste

Range("B696").Select

ActiveSheet.Paste

Range("B746").Select

ActiveSheet.Paste

Range("B796").Select

ActiveSheet.Paste

Range("B846").Select

ActiveSheet.Paste

Range("B896").Select

ActiveSheet.Paste

Range("B946").Select

ActiveSheet.Paste

Range("B996").Select
```

```
ActiveSheet.Paste

Range("B1046").Select

ActiveSheet.Paste

Range("B1096").Select

ActiveSheet.Paste

Range("B1146").Select

ActiveSheet.Paste

Range("B1196").Select

ActiveSheet.Paste

Range("A47").Select

Range("A47:IQ47").Select

Selection.Copy

Sheets("Sheet2").Select

Range("A1").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(251, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(49, 1).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

ActiveCell.Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select
```

```
Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
```

```
    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(49, 0).Range("A1:IP1").Select
```

```
Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(51, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(49, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
```

```
    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(51, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select
```

```
Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

    :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
```

:=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

  :=False, Transpose:=True

ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

  :=False, Transpose:=True

  ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _

  :=False, Transpose:=True

  ActiveCell.Offset(250, 0).Range("A1").Select

Sheets("Sheet1").Select

ActiveCell.Offset(50, 0).Range("A1:IP1").Select

```
Application.CutCopyMode = False

Selection.Copy

Sheets("Sheet2").Select

Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=True

Range("C1").Select

ActiveCell.FormulaR1C1 = "Time"

Range("D1").Select

ActiveCell.FormulaR1C1 = "Cal_Slope"

Range("D2").Select

ActiveCell.FormulaR1C1 = "=(RC[-3]*-1.7949) + 0.5356"

Range("D2").Select

Selection.AutoFill Destination:=Range("D2:D6001"), Type:=xlFillDefault

Range("D2:D6001").Select

Range("D6001").Select

Range("C1:D6001").Select

Range("D6001").Activate

Charts.Add

ActiveChart.ChartType = xlXYScatter

ActiveChart.SetSourceData Source:=Sheets("Sheet2").Range("C1:D6001")

ActiveChart.Location Where:=xlLocationAsObject, Name:="Sheet2"

ActiveWindow.Visible = False

Range("D6001").Select

ActiveSheet.ChartObjects("Chart 1").Activate

ActiveChart.ChartArea.Select

ActiveSheet.Shapes("Chart 1").IncrementLeft 155.25

ActiveSheet.Shapes("Chart 1").IncrementTop -66863.25
```

End Sub

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