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READING, CONTRAST ADAPTATION AND ACCOMMODATION IN YOUNG ADULT MYOPES AND EMMETROPES.

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ABSTRACT

FACULTY OF SCIENCE AND TECHNOLOGY

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READING, CONTRAST ADAPTATION AND ACCOMMODATION IN YOUNG ADULT MYOPES AND EMMETROPES.

By COLM D. MCGONIGLE

2016

Numerous reports associate prolonged periods of near-work and specifically reading with myopia development. The exact mechanisms that underpin this relationship are however, unclear. Reading may induce perceptual adaptations, specifically changes in contrast sensitivity and to the accuracy of the accommodation response. Reduced contrast sensitivity and accommodation may degrade retinal image quality which could result in a stimulus to ocular elongation and therefore myopia.

The experimental work undertaken in this thesis investigated whether reading text on a screen influenced changes in contrast sensitivity (contrast adaptation) and accommodation differently in young adult emmetropic and myopic participants. Contrast adaptation was examined for spatial frequencies, including those created by text rows and character strokes, and accommodative accuracy was determined before and after reading. Furthermore, the influence of cognitive effort on such changes was explored by comparing adaptation to an incomprehensible phase randomised stimulus that otherwise shared the statistical properties of the text stimulus.

Reading text on a screen induced contrast adaptation at the spatial frequency created by text rows and myopic participants incurred more than twice the adaptation of emmetropes. Contrast adaptation was not significant at the spatial frequency created by character strokes in either participant group. Myopic participants had significantly greater accommodative lag (reduced accuracy) than emmetropes after reading text. Myopes also showed a significant increase in accommodative lag after reading.

There was no significant change in contrast sensitivity or accommodative accuracy after participants viewed the phased randomised stimulus.

Text stimuli are inherently dominated by low, narrowband and orientation constrained spatial frequencies generated by row of letters and inter-row space. The results presented show myopes to be more susceptible to adaptation to these specific text characteristics as a consequence of active reading. However, there is extensive scope for further work to determine precisely why this is the case and how such changes may engender myopia development.

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READING, CONTRAST ADAPTATION AND ACCOMMODATION IN YOUNG ADULT MYOPES AND EMMETROPES.

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Abbreviations

ABIAS	Tonic accommodation/accommodative bias
ACG	Accommodative controller gain
AFC	Alternative forced choice
AE	Accommodative error
ANS	Autonomic nervous system
AS	Accommodative stimulus
ASG	Accommodative sensory gain
AR	Accommodative response
CA	Vergence accommodation
COV	Co-efficient of variation
cdeg^{-1}	Cycles per degree visual angle
D	Dioptre
Dh	Dioptre hour
DPI:	Dots per inch
DSP	Depth of focus
FFT	Fast Fourier Transform
Fmri	Functional magnetic resonance imaging
HVS	Human visual system
IRDT	Incremental retinal defocus theory
LGN	Lateral geniculate nucleus
$\log_{10}$CS:	log contrast sensitivity
NITM	Near-work induced transient myopia
PAL	Progressive add lens
PDF:	Probability density function
PERG	Pattern electroretinogram
qCSF	Quick contrast sensitivity function
RMS	Root mean square
SEM:	Standard error of the mean
SER:	Spherical equivalent refraction
SD:	Standard deviation
VEP	Visual evoked potential

Chapter 1
Introduction

Myopia's threat to vision throughout the world is growing (Wong, Ferreira, Hughes, Carter & Mitchell, 2014). An association between near work and myopia was first proposed in the 17th Century by Johannes Kepler who observed that, "*those who do near work in their youth become more myopic,*" (Mark, 1971). Two centuries later, reports by Ware (1813) and Cohn (1886) reinforced the proposition by presenting statistics that showed an increase in myopia prevalence amongst children, university students and army recruits who had undertaken more intensive and higher degrees of education. Donders and Moore (1864) and von Helmholtz (1867) believed that myopia resulted from excessive near work.

Near work is frequently cited as being myopigenic (Saw, Hong, Chia, Stone & Tan, 2001; Saw et al., 2001a; Mutti, Mitchell, Moeschberger, Jones & Zadnik, 2002; Saw et al., 2002) and epidemiological studies have found a significant correlation between the incidence of myopia and increasingly competitive and rigorous education systems that involve prolonged periods spent reading (see Morgan, Ohno-Matsui & Saw, 2012 for a review).

1.1 Myopia Definition

Myopia (also referred to as short or near sightedness) is a type of refractive error and causes difficulty seeing distant objects clearly. When a myopic eye is in a non-accommodated state, light rays from an object at infinity converge too strongly and focus in front of the retina (Figure 1.1). This is either due to the refractive power being too strong or the eye being too long and the retinal image is therefore perceived as blurred.
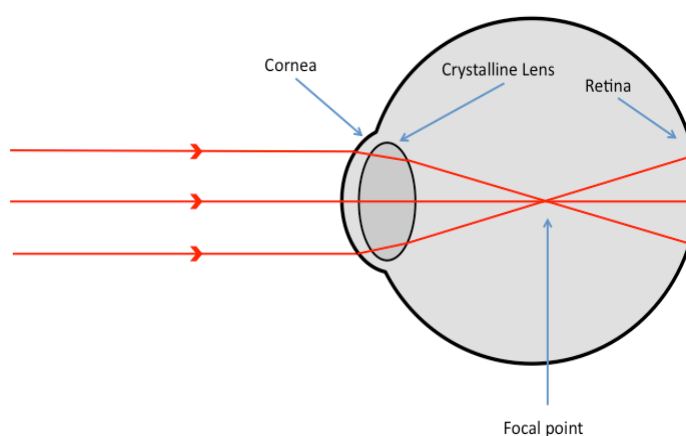
Figure 1.1: The refractive power of a myopic eye is too strong and the focal point of light rays is in front of the retina.

1.2 Myopia prevalence and epidemiology

1.2.1 Prevalence

It is estimated that there are 1.7 billion people worldwide with myopia, 80 million of whom are children aged between 8 and 12 years (Siatkowski et al., 2008). This is expected to rise to 2.5 billion by 2020 (Kempen et al., 2004) and 5 billion (half of the World's population) by 2050 (Holden et al., 2015). The prevalence of myopia has doubled in the USA and Europe over the last 50 years (Dolgin, 2015) and it has reached epidemic levels in South East Asia (Sood & Sood, 2014). It varies greatly between different populations and ethnic groups. A multi-centre study by Kleinstein et al. (2003) in the USA compared the prevalence among three ethnic groups of school children aged between 5-17 years, and found that 18.5% of Asians had myopia compared to only 6.6% of African Americans and 4.4% of Caucasians. In Singaporean military conscripts aged from 16-25, 82% of those of Chinese ethnicity were myopic compared to 69% of Indian and 65% of Malayan ethnicity (Wu et al., 2001). In comparison, the prevalence of myopia is lower amongst Finnish military conscripts of a similar age (17-30 years) at only 22% (Vannas et al., 2003).

Longitudinal studies reveal increasing myopia prevalence throughout the world: Hung (2001) reported that between 1983 and 2000, myopia increased from 5.8% to 21% in 7 year olds, from 36.7% to 51% in 12 year olds, from 64% to 81% in 15 year olds, and from 74% to 84% in 16-18 year olds in Taiwan; in Japan, Matsumura and Hirai (1999) found myopia rates in 17 year olds increased from 50% to 66% over 13 years; in the USA, Vitale, Sperduto and Ferris (2009) found that myopia increased from 25% (1971-72) to 41.6% (1999-2004) in 12-54 year olds; in the UK, McCullough, O'Donoghue and Saunders (2016) concluded that the proportion of myopic children aged between 10-16 years has doubled over the last 50 years and that children are becoming myopic at a younger age. The National Eye Institute estimated that there were 34 million myopes in the USA in 2010, which is projected to increase to 44 million by 2050 (Holden, Davis, Jong and Resnikoff, 2014).

Table 1.1 shows a selection of data for myopia prevalence in various countries across four continents, and the risk factors attributed to myopia onset. The variation in sampling methodology must be taken into account; however, what is apparent is that myopia is most pervasive in East Asia or populations of East Asian descent. In these countries, myopia has been reported in children as young as 4 years old, and has been linked to the early commencement of competitive and intensive schooling (Saw et al., 2005). Furthermore, those who acquire the highest degrees of education also display higher rates of myopia (Chew, Chia & Lee, 1988; Chow, Dhillon, Chew & Chew, 1990; Wu et al., 2001).

Country	Authors and year	Cohort			Prevalence	Causative factor
		Group	Size	Age (years)		
Singapore	Chow et al., 1990	Medical students	128	20-22	82%	IQ Near work
	Tay, Au, Ng and Lim, 1992	Males	421,116	15-25	1974-1978: 26% 1987-1991: 43.3%	Education
	Zhang et al., 2000	City school children	146	6-7	12.3%	Environment
	Wu et al., 2001	Military conscripts	15,095	16-25	79.3%	Education
	Pan et al., 2013a	Singaporean adults	10,033	40-80	38.9%	Chinese ethnicity
Hong Kong	Lam and Goh, 1991	High school students		17	74%	Education
	Lam et al., 1994	Adults (community workers union)	220	40-64	27.2%	Not specified
	Lam, Edwards, Millodot and Goh, 1999	School children	142	6-17	62%	Not specified
	Fan et al., 2004	School children	7560	5-16	36.71%	Genetics Environment
	Lam, Lam, Cheng and Chan, 2012	School children	2883	6 12	18.3% 61.5%	Not specified

Country	Authors and year	Cohort			Prevalence	Causative factor
		Group	**Size**	**Age (years)**		
USA	Wang, Klein, Klein and Moss, 1994	Adults	4926	43-84	26.2%	Education
	Katz, Tielsch and Sommer, 1997	Black and white adults	5028	40-89	Black: 19.4% White: 28.1%	Education
	Kleinstein et al., 2003	School children	2523	5-17	9.2%	Ethnicity, education, age
	Vitale, Ellwein, Cotch, Ferris and Sperduto, 2008	Adults	12,010	20-50	38.4%	Not specified
	Pan et al., 2013b	Adults	4430	45-84	25.1%	Chinese ethnicity
UK	Rahi, Cumberland and Peckham, 2011	Adults	2487	44	49%	Birth order, older mothers, smoking during pregnancy, higher socio-economic status.
	Cumberland et al., 2015	English and Welsh Adults	107,452	40-69	27%	Higher socio-econmoic status, higher educational attainment, White or Chinese ethnicity
	McCullough et al., 2016	Northern Irish children	438	12-20	12-13 years: 16.4% 18-20: 18.6%	Education

Country	Authors and year	Cohort			Prevalence	Causative factor
		Group	Size	Age (years)		
Taiwan	Lin, Shih, Hsiao and Chen, 2004	High school students	2474	16-18	84%	Education
	Lee, Lo, Sheu and Lin, 2013	Military conscripts	5048	18-24	86.1%	Education, time spent reading, closer working distance, myopic parents
South Korea	Jung, Lee, Kakizaki and Jee, 2012	Army conscripts from metropolitan area	23,616	19	96.5%	Education
	Lee, Jee, Kown and Lee, 2013	Rural males	2805	19	83.3%	Environment
China	Liang et al., 2009	Rural adults	6491	30+	26.7%	Genetics, near work, education
	Sun et al., 2012	University students	5083	14-42	95.5%	Education, age, females, ethnicity
	Zhou et al., 2016	School children	3469	6-15	54.9%%	Age, females
Australia	Wensor, McCarty and Taylor, 1999	Adults	3271 urban 1473 rural	40-98	17%	Education, age, race
	French, Morgan, Burlutsky, Mitchell and Rose, 2013	Sydney schoolchildren	2072	12-17	12 years: 14.4% 17 years: 29.6%	Environment, race

Country	Authors and year	Cohort			Prevalence	Causative factor
		Group	Size	Age (years)		
Norway	Midelfart, Kinge, Midelfart and Lydersen, 2002	Young and middle aged adults	1248 1889	20-25 40-45	35.0% 30.3%	Not specified
Finland	Vannas et al., 2003	Army conscripts	3524	17-30	22.2%	Genetics Education
Mexico	Villarreal, Ohlsson, Cavazos, Abrahamsson and Mohamed, 2003	School children	1035	12-13	37%	Genetics Environment
Japan	Matsumura and Hirai, 1999	High school students	9420	17	65.6%	Education
Greece	Mavracanas et al., 2000	High school students	1738	15-18	36.8%	Near work Education
Denmark	Jacobsen, Jensen and Goldschmidt, 2007	Army conscripts	3294	17-20	12.8%	IQ Education

Table 1.1: Myopia prevalence throughout the world with attributed causative factors.

1.2.2 Epidemiology and socio-economic consequences

The increasing prevalence of myopia has direct socioeconomic implications resulting in billions of dollars of lost productivity globally (Smith, Frick, Holden, Fricke & Naidoo, 2009). It has been estimated that myopic Singaporeans annually spend US$90 million on spectacles and US$2.5 million on refractive surgery (Seet et al., 2001). In the USA, the direct cost of myopia was estimated to be US$12.8 billion in 1990 (Javitt & Chiang, 1994). Additionally, access to eye care is often restricted in rural areas of developing countries (Naidoo et al., 2010; He et al., 2012; Naidoo & Jaggernath, 2012) leaving many myopes uncorrected. Furthermore, myopes may be restricted in their choice of profession due to the stipulation for a specific level of uncorrected vision including the aviation industry, fire officers, LGV drivers and the military (Royal College of Ophthalmologists: ophthalmic service guidance, 2016). Such restrictions and limitations emphasise the importance of the need for a better understanding of the aetiology of myopia to limit the high prevalence and associated socio-economic implications.

1.2.3 Ocular complications of myopia

Myopia is associated with an increased risk of serious and potentially sight threatening ocular pathologies, including cataract (Kanthan, Mitchell, Rochtchina, Cumming and Wang, 2014; Pan et al., 2013b), retinal detachment (Bier, Kampik, Gandorfer, Ehrt & Rudolph, 2010; Mitry et al., 2009), choroidal neovascularisation (reviewed by Saw, Gazzard, Shih-Yen & Chua, 2005), glaucoma (review by Marcus, De Vries, Montolio & Jansonius, 2011) and myopic maculopathy (Liu et al., 2010). Pathologic myopia has been reported as the primary cause of blindness or low vision in 7% of cases in European populations (Cedrone et al., 2006; Klaver, Wolfs, Vingerling, Hofman & de Jong, 1998) and 12-27% in Asian populations (Iwase et al., 2006). Myopic maculopathy has even been reported as the leading cause of blindness in certain regions of China (Wu, Sun, Zhou & Weng, 2011) and Japan (Iwase et al., 2006). Complications from pathologic myopia are a major cause of visual impairment (Ohno-Matsui, Lai, Lai & Cheung, 2016).

1.3 Aetiology of myopia

Myopia aetiology is multi-factorial; however, the causative factors can be broadly grouped into either genetic or environmental theories. Studies involving twins (monozygotic and dizygotic), familial incidence, and the distribution of refractive errors in rural communities and ethnic populations have convincingly established the role of heritable factors in refractive development (Wojciechowski, 2011). Yet epidemiological studies have also found that the progression of myopia is moderated by environment and lifestyle (Day & Duffy, 2011).

1.3.1 Genetics

The utilisation of twins to evaluate the influence of genetics versus environment dates back to when Galton (1876) first introduced the term, "*nature versus nurture*," and it is proposed that there is interaction between the two in the aetiology of myopia. Genetic predisposition to myopia has been well documented (Ashton, 1985; Goss, Hampton & Wickham, 1988; Mutti & Zadnik, 1995; Pacella et al., 1999; Wu & Edwards, 1999; Guggenheim, Kirov & Hodson, 2000; Saw et al., 2001b; Mutti et al., 2002; Czepita, Moisa, Ustianowska, Czepita & Lachowicz, 2010; Verhoeven et al., 2012). Studies have shown an increased risk of myopia in children when both parents are myopic, and less when one is myopic (Morgan & Rose, 2005; Kurtz et al., 2007; Konstantopolous, Yadergarfar & Elgohary, 2008, Lam et al., 2008). Heritability for myopia in twin studies has generally been high (Sanfilippo, Hewitt, Hammond & Mackey, 2010): a study by Hammond, Sneider, Gilbert and Spector (2001) showed higher correlation of refractive error between monozygotic twins than dizygotic twins. Twins typically have shared environments as well as shared genes. In these instances, myopia cannot be attributed solely to genetics. Although chromosomal loci have been established for non-pathological and syndromic (e.g. Stickler, Marfan, Knobloch syndromes) high myopia, there is no known gene associated with physiological myopia (Hornbeak & Young, 2009). Little can be done to modify heritability but the increasing need to retard myopia progression highlights the need for better understanding of environmental influences.

1.3.2 Environment

Angle and Wissmann (1980) suggested that at least a portion of myopia is not genetic and therefore preventable. Epidemiological studies in developed countries correlate higher rates of myopia with increasingly competitive and rigorous education systems (Goldschmidt, 1968; Wong, Coggon, Cruddas & Hwang, 1993; Wang et al., 1994; Wensor et al., 1999; Saw et al., 2001a; Saw et al., 2001b, Shimizu et al., 2003; Williams & Hammond, 2014), and specifically to prolonged periods of near work (Angle & Wissman, 1980; Zylbermann, Landau & Berson, 1993; Kinge, Midelfart, Jacobsen & Rystad, 2000; Saw et al., 2002; Mutti et al., 2002; Huang, Chang & Wu, 2015), and the distance at which close work is undertaken (Ip et al., 2008). These studies allude to a strong environmental influence on refractive development. Table 1.2 references additional behavioural and environmental risk factors identified as being myopigenic.

Myopia risk factor	References
Higher IQ	Teasdale, Fuchs and Goldschmidt, 1988
	Mutti et al., 2002
	Saw et al., 2004
	Saw et al., 2006
Higher socio-economic status	Wong, Foster, Johnson and Seah, 2002
Urbanisation	He, Huang, Zheng, Huang and Ellwein, 2007
	Zhang et al., 2010
Protective effect of outdoor activity	Jones et al., 2007
	Rose et al., 2008a
	Dirani et al., 2009
	Yi and Li, 2011
	Guggenheim et al., 2012
	He et al., 2015
	Ramamurthy, Chua, Yu and Saw, 2015
Occupation: near tasks	Simensen and Thorud, 1994
	McBrien and Adams, 1997
Diet: higher saturated fat and cholesterol intake	Lim et al., 2010
Birth season: Summer and Autumn	Mandel et al., 2008
	Ma, Xu, Zhou, Cui, and Pan, 2014
Higher birth order	Rudnicka, Owen, Richards, Wadsworth and Strachan, 2008
	Guggenheim et al., 2013
Lower post-natal light levels	McMahon et al., 2009
	Deng and Gwiazda, 2011
Maternal smoking during pregnancy	Saw, Chia, Lindstrom, Tan and Stone, 2004
	Iyer, Low, Dirani and Saw, 2012

Table 1.2: Environmental and behavioural risk factors identified as being myopigenic.

The aforementioned environmental and behavioural risk factors have been suggested to have a myopigenic effect. Significantly greater rates of myopia have repeatedly been shown for ethnicity and aged-matched individuals living in urban as opposed to rural locations in the same country (Saw, et al., 2001b; Ip et al., 2008; Czepita, Mojsa & Zejmo, 2007; Uzma, Kumar, Salar, Zafar & Reddy, 2009). A study by Rose et al., (2008b) showed variation in the prevalence of myopia amongst individuals of the same ethnic or racial group living in different countries and found a significantly higher prevalence of myopia for children with two Chinese parents living in Singapore (29.1%) than in Sydney (3.3%). Whether this is due

to inter-ethnic differences in the genetic predisposition to myopia or to culture-specific environmental influences remains uncertain. Morgan, Speakman and Grimshaw (1975) reported a myopia epidemic amongst genetically homogenous Canadian Inuit's in the 1970's: a significantly greater prevalence of myopia was observed over a single generation where the younger members' attendance at school was indicated as an aetiologic factor. Morgan and Rose (2005) suggest that a genetic predisposition for myopia may be triggered by an individual's environmental exposures. Conversely, the incidence of myopia is minimal in small towns in Africa (Yared, Belaynew, Destaye, Ayanaw & Zelalem, 2012) and South America (Ibrahim et al., 2013) where education is limited.

A plethora of both prospective studies and randomised clinical trials allude to the protective effect of time spent outdoors (reviewed by Ramamurthy et al., 2015). A recent meta-analysis went so far as to suggest a 2% reduction in the odds of myopia development for each additional hour spent outdoors per week (Sherwin et al., 2012). Huang et al. (2015) found that more time spent on near work activities was associated with higher odds of myopia, specifically that the odds of myopia increased by 2% for every one dioptre-hour more of near work per week [dioptre hour, $Dh = 3 \times$ (hours spent studying + hours spent reading for pleasure) + $2 \times$ (hours spent playing video games or working on the computer at home) + $1 \times$ (hours spent watching television); Mutti et al., 2002].

Education, socioeconomic status, and occupation are generally considered to be indirect surrogates for more proximal risk factors such as near-work visual demand and other unmeasured environmental variables (Wojciechowski, 2011). Studies of the effect of reading have attempted to show a more direct relationship between myopia and near work (Saw et al., 2001; Mutti et al., 2002; Saw et al., 2002; Jones-Jordan et al., 2011; You et al., 2012; French, Morgan, Mitchell & Rose, 2013; Guo et al., 2013a; Guo et al., 2013b; Lee, Lo, Sheu & Lin, 2013; Gong, Zhang, Tian, Wang & Xiao; 2014).

1.4 Development of Myopia

Numerous lines of evidence from experimental myopia models and epidemiological studies have demonstrated that environmental exposure plays a crucial role in ocular growth and refractive development. The precise biological mechanisms through which the environment influences ocular refraction in humans are, however, still a matter of debate.

1.4.1 Emmetropisation and animal models

Emmetropisation is the process in humans and other animals by which the power of the anterior segment of the eye (cornea and crystalline lens) develops sufficient refractive power to focus light rays from infinity exactly on the retina (reviewed in Wildsoet, 1997). Gwiazda, Thorn, Bauer and Held, (1993a) suggested the process exists to prevent the

development of refractive error by controlling eye growth earlier in life. Animal models (reviewed by Wallman & Winawer, 2004) in chickens and non-human primates first developed towards the end of the last century have helped further understanding of normal eye growth processes and the influence of the environment on refractive error development in humans.

Studies have interrupted the process of emmetropisation by *form deprivation* using diffusing lenses (Wallman & Adams, 1987), eyelid sutures (Smith, Bradley, Fernandes & Boothe, 1999; Trolio, Nickla & Wildsoet, 2000), and spherical lenses (Schaeffel, Glasser & Howland, 1988; Smith & Hung, 2000) in monkeys, chicks and marmosets. Negative spherical lenses have also been used to induce hyperopic defocus that has been shown to produce myopia (Irving, Callender & Sivak, 1991; Irving, Sivak & Callender, 1992; Wildsoet, 1997; Smith & Hung, 1999; Zhu, Park, Winawer & Wallman, 2005). The negative lenses focus the image plane behind the retina and the consequent visual deprivation is thought to act as a stimulus to ocular elongation resulting in excessive eye size and therefore myopia (Figure 1.2).
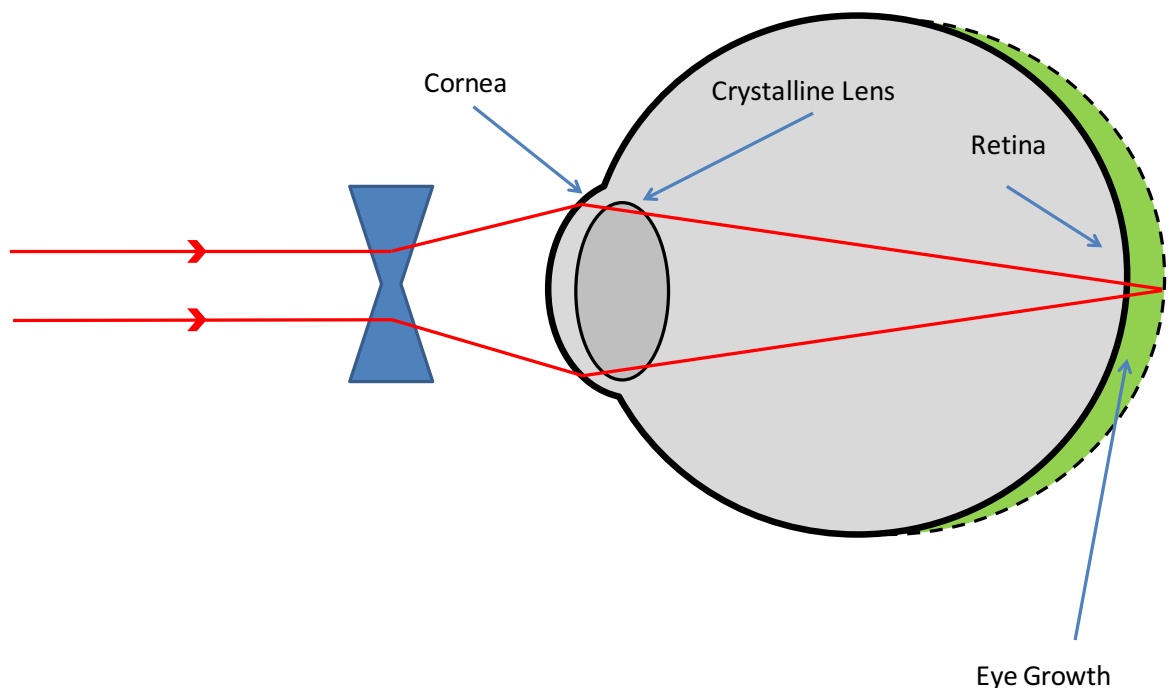
Figure 1.2: A negative lens in front of an emmetropic eye will focus light behind the retina which acts as a stimulus to ocular elongation.

In studies on tree shrews (Siegwart & Norton, 1999) and monkeys (Smith & Hung, 2000), the removal of diffusing lenses (which removed the visual deprivation) slowed ocular elongation and refraction returned to normal. Arresting ocular elongation and myopia progression was also shown in chicks (Schmid & Wildsoet, 1996), tree shrews (Shaikh, Siegwart & Norton, 1999), marmosets (Whatham & Judge, 2001), and infant monkeys

(Smith & Hung, 1999). These findings suggest that the ocular growth process can be visually guided, adapts in response to defocus, and is locally guided (i.e. within the retina) (Wallman, Gottlieb, Rajaram & Fugate-Wentzek, 1987). Further evidence of emmetropisation regulation at a retinal level comes from studies where form deprivation still occurred after the optic nerves of monkeys and chicks were sectioned (Raviola & Weisel, 1985; Troilo, Gottlieb & Wallman, 1987). The findings of all these studies emphasise that a good quality visual signal is critical for normal ocular development.

1.4.2 Human models

Animal studies have helped our understanding of normal eye growth processes and the influence of the environment on refractive error development. This has led to interest in defocus blur and its relevance to myopia in humans resulting in a plethora of studies over the last 20 years. There has been an implicit acceptance that prolonged accommodation and retinal image defocus blur promote eye growth as a consequence of accommodative inaccuracies (Gwiazda, Thorn, Bauer & Held, 1993b; Gwiazda, Bauer, Thorn & Held, 1995a; Jiang, 1997; Abbott, Schmid & Strang, 1998; Gwiazda et al., 2004; Harb, Thorn & Troilo, 2006; Allen & O'Leary, 2006; Langaas et al., 2008; Strang, Day, Gray & Seidel, 2011; Feldkaemper & Schaeffel, 2013; Smith, Hung & Arumugam, 2014; Sankaridurg & Holden, 2014; Schmid & Strang, 2015; Hung, Mahadas & Mohammad, 2016). This, in turn, results in hypermetropic retinal blur which increases in tandem with accommodative lag (see section 1.6.5) and acts as a stimulus for ocular growth culminating in myopia progression. It must also be acknowledged that this hypothesis has been disputed by Mutti et al. (2006), Weizhong, Zhikuan, Wen, Xiang and Jian (2008) and Bernsten, Sinnott, Mutti and Zadnik (2011). Mutti et al. (2006) and Bernsten et al. (2011) suggest that the hypermetropic defocus is a correlate rather than a cause of myopia, and propose a theory whereby ocular mechanical factors (ciliary-choroidal tension) increases as the eye grows until it reaches a limit. This prevents further equatorial expansion which then accelerates axial growth and myopia development.

In humans, a deficit in accommodative response (see section 1.6.5) is analogous to negative lens induced defocus in animal studies. Ethical considerations limit the manipulation of the emmetropisation process in humans as examined in animal studies, however comparison can be drawn from studies which demonstrate increased myopia development in subjects with neonatal ptosis, fused eyelids and corneal opacification (Robb, 1977; Hoyt, Stone, Fromer & Billson, 1981; Rabin, Van Sluyters, & Malach, 1981; Gee & Tabbara, 1988).

Wallman and Winnawer (2004) summarised that control of eye growth in chicks comes from the retina, which itself encompasses an entire sensorimotor apparatus by interpreting blur

and moving itself forward and backward within the eye. Adler and Millodot (2006) questioned the validity of applying the results of animal studies to humans and suggested that the presence of blurred vision at any distance may stimulate the progression of myopia regardless of the sign of defocus.

The following sections of this chapter introduce the perceptual phenomenon of contrast adaptation and details the physiological accommodation response of the eye. Near-work, specifically reading, may alter these responses: latter sections of the chapter consider how such alterations may induce retinal image defocus which gives rise to retinal error signals controlling eye growth, and therefore myopia development in humans.

1.5 Neural interpretation of our visual percept

1.5.1 Fourier analysis

Fourier (1822) demonstrated that a periodic waveform of any complexity can be decomposed into a linear sum of harmonically related sine waves of specified frequencies, amplitudes and phases. The application of Fourier analysis provides a means by which complex waveforms or shapes can be interpreted quantitatively. The sine wave (a fundamental transcendental periodic function) is the fundamental element of Fourier analysis. In two-dimensional spatial vision, sine waves are characterised as oscillations across space (Figure 1.3).
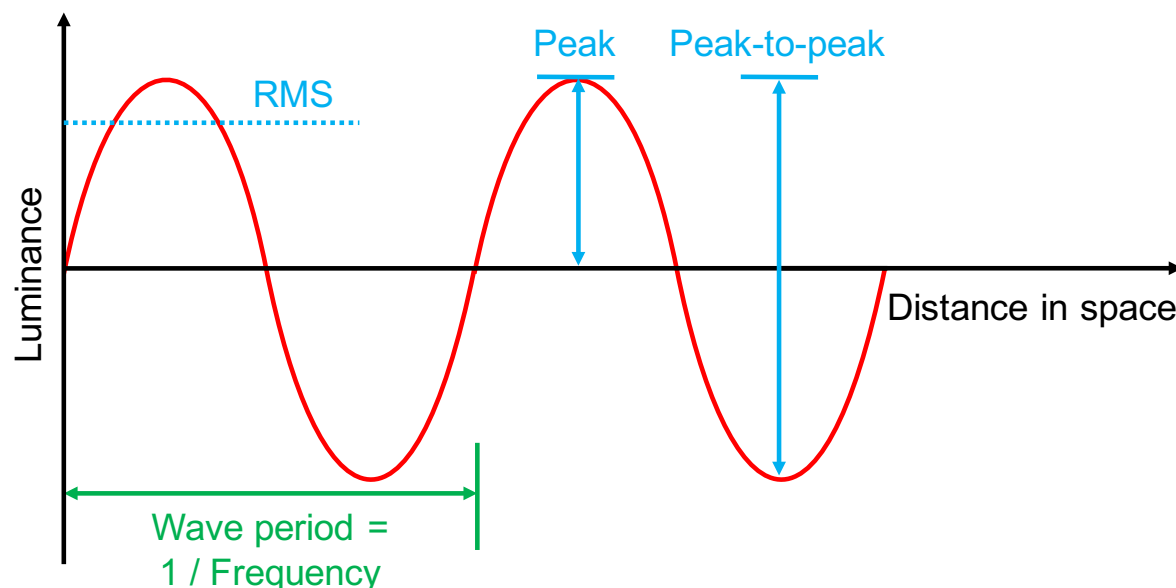
Figure 1.3: A sine wave, characterised by its period (1/frequency) and amplitude.

Spatial frequency can be broadly defined as an oscillation of luminance or colour in space (DeValois & DeValois, 1990). The frequency of a sine wave in the spatial domain is the number of oscillations per unit distance: visual stimuli are specified in terms of the visual angle subtended at the eye and thus, the specification of spatial frequency in the context of vision science is in cycles per degree of visual angle (cdeg^{-1}).

Figure 1.3 illustrates the numerous definitions applied to the measurement of the amplitude of a waveform. Peak amplitude is the maximum excursion of the wave from the zero or equilibrium point. Peak-to-peak amplitude is the distance from a negative peak to a positive peak (exactly twice the peak amplitude value as the sine waveform is symmetrical). Root Mean Square (RMS) amplitude is used in calculations involving the power of the waveform and is the square root of the average of the squared values of the waveform. In the case of the sine wave, $RMS = Peak \div \sqrt{2} \approx 0.707 \times Peak$.

Waves are typically described by their power (the amplitude squared). Like amplitude, contrast is a measure of the height of a waveform and is often measured using the Michelson definition $C_{mich} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$ where L_{max} is the maximum luminance (white bars) and L_{min} is the minimum luminance (black bars) of the sine wave grating.

Phase is the third variable of the Fourier Transform, and refers to the position of the sinusoidal wave with respect to a reference point. Figure 1.4 illustrates absolute phase whereby sine waves of equal frequency and amplitude differ in their respective positions on the x-axis. Relative phase refers to the relative phase angle (difference in the absolute phase) amongst multiple frequencies in a pattern, and it is this which will be considered later in this thesis. Power spectrum is the power at each of the various constituent spatial frequencies within a visual stimulus, irrespective of phase.
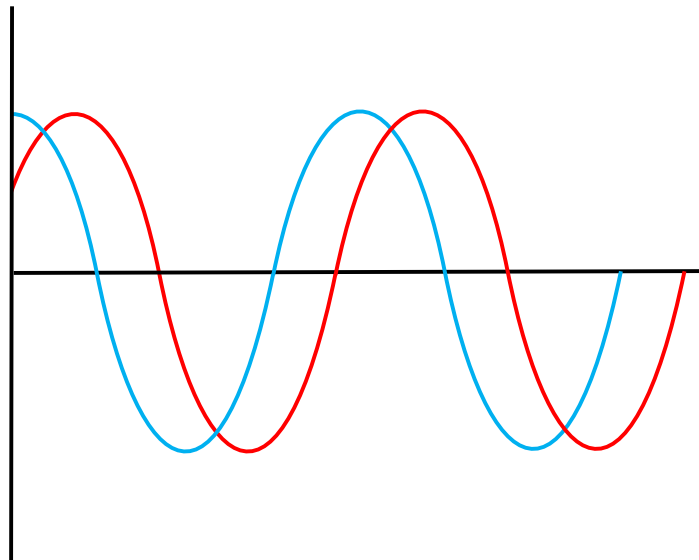
Figure 1.4: Sine waveforms of equal frequency and amplitude but their phase differs by 90°.

1.5.2 Contrast sensitivity

Contrast sensitivity is the ability to discern between luminance of different levels within a static image. Human ability to detect spatial frequencies of varying contrasts is an informative parameter of the capability of the visual system (more so than measurements

of visual acuity), as our world is composed of different luminances. Contrast is expressed as a percentage from 0%-100%: visual acuity is a measure of the angle at which an observer can detect two separate objects at only 100% contrast; measurement of the contrast sensitivity function involves measuring sensitivity to sine wave gratings of varying contrast. The amount of contrast an observer requires to detect a grating is denoted as the contrast threshold, the reciprocal of which is contrast sensitivity at that particular spatial frequency.

1.5.3 Contrast sensitivity function

Schade (1956) made the first measurements of visual contrast sensitivity as a function of test spatial frequency with the co-ordinates plotted on a log scale. Figure 1.5 shows the typical bandpass filter of the human contrast sensitivity function (CSF): it illustrates the variation in sensitivity across a range of spatial frequencies and peak sensitivity in the region of $4cdeg^{-1}$, indicating that gratings displayed at $4cdeg^{-1}$ will be detected at lower contrast than other frequencies.
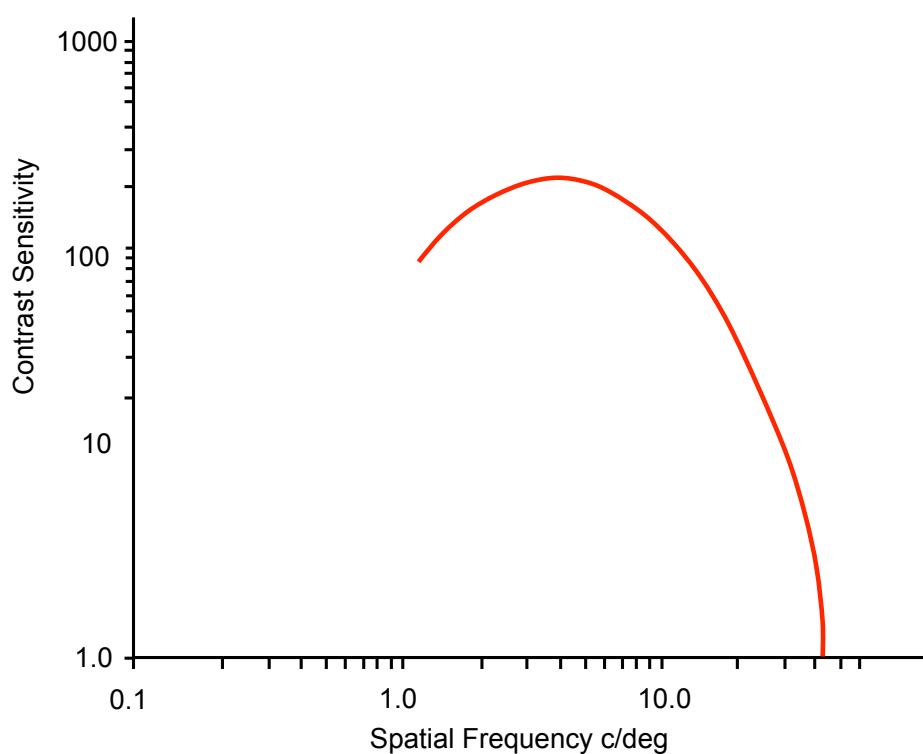
Figure 1.5: Sample human contrast sensitivity function, reproduced from Schwartz, (2009).

1.5.4 Neural interpretation

The human visual system (HVS) can be thought of as a Fourier analyser in which the visual percept (consisting of a plethora of spatial frequency information) is interpreted by individual spatial frequency channels (Campbell & Robson, 1968), each channel selective to a narrow range of spatial frequencies. In psychophysical studies, a channel refers to a filtering mechanism whereby some, but not all of the information that may impinge on it is passed

through. These individual spatial frequency components are then reassembled to form a unified visual percept.

Each of these narrowly tuned filters is responsive to only some fraction of the total range encompassed by the CSF of the observer as illustrated in Figure 1.6 which highlights that each channel is specific to low, mid and high spatial frequencies (Levine & Shefner, 1991). Sensitivity to bands of orientation specific spatial frequencies has also been shown in the visual cortex of the cat, further evidencing the physiological correlates from psychophysical experiments (Hubel & Weisel, 1962; Campbell, Cooper & Enroth-Cugell, 1969).
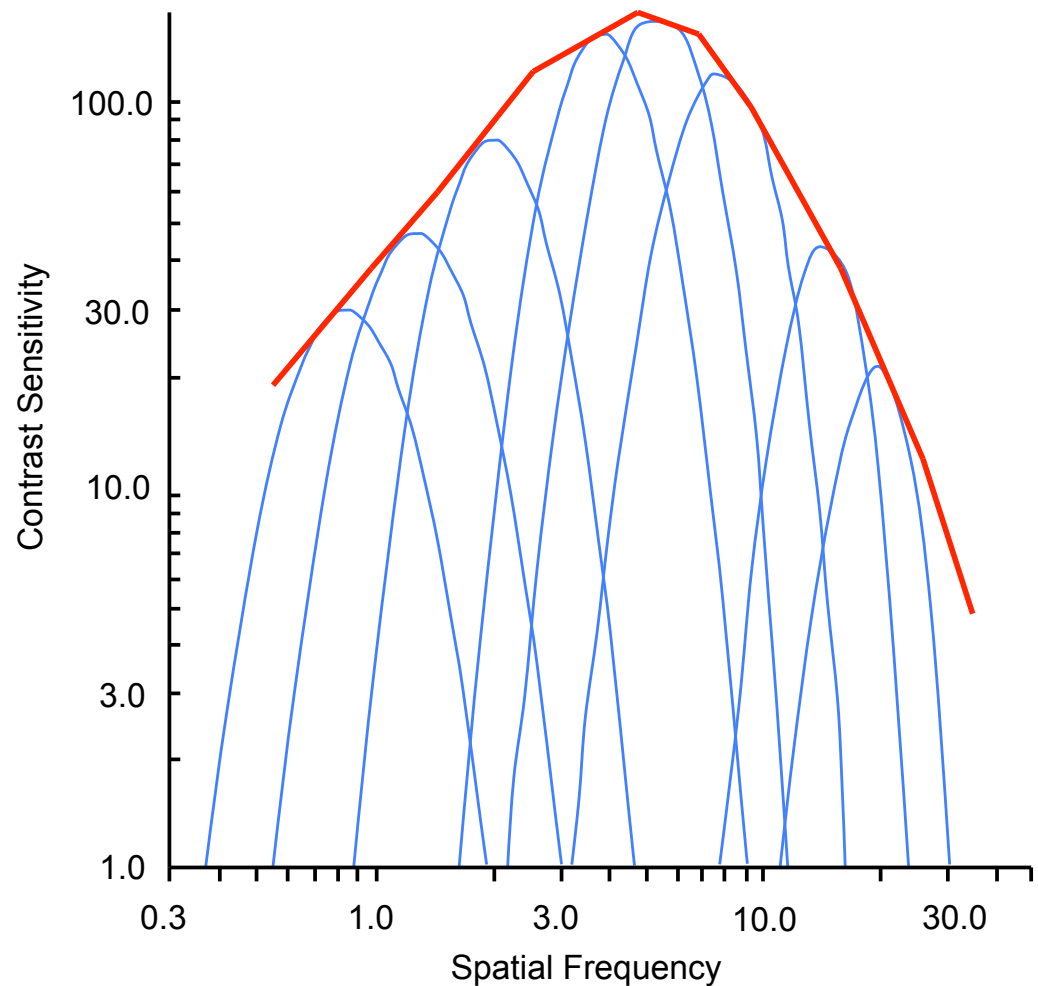
Figure 1.6: Spatial frequency sensitivity function as the envelope of many more narrowly tuned spatial frequency selective channels (reproduced from De Valois & De Valois, 1990).

The change in contrast sensitivity following prolonged exposure to a grating stimulus described by Blakemore and Campbell (1969) is considered a perceptual adaptation and is paralleled by decreases in firing rates of neurons in V1 (Gardner et al, 2005). Goldstein (2007) suggests this adaptation is a consequence of neuronal firing fatigue which correlates well with the psychophysical concept of contrast adaptation.

1.5.5 Contrast Adaptation

Contrast adaptation is a change in contrast sensitivity at specific spatial frequencies that occurs in response to prior exposure to a similar spatial frequency distribution contained in an adaptor target that has been viewed over a prolonged period (Blakemore & Campbell, 1969; Blakemore, Nachmias & Sutton, 1970; Blakemore, Muncey & Ridley, 1973). Contrast adaptation can be orientation specific (Blakemore & Campbell, 1969; Blakemore & Nachmias, 1971), and corresponds to the spatial frequency content of the adapting stimulus (Pantle & Sekuler, 1968; Blakemore, Muncey & Ridley, 1971). Contrast adaptation can also be explored through interocular transfer (Blakemore & Campbell, 1969) which, in addition to orientation specificity, is indicative of a cortical locus for adaptation.

Blakemore and Campbell (1969) also showed that the magnitude of adaptation is greater for a higher contrast adaptor target: a high contrast grating 1.25 log units above threshold resulted in up to a 3 times increase in log contrast threshold elevation (contrast sensitivity depression) compared to just over 2 times increase for a target 0.75 log units above threshold (Figure 1.7).
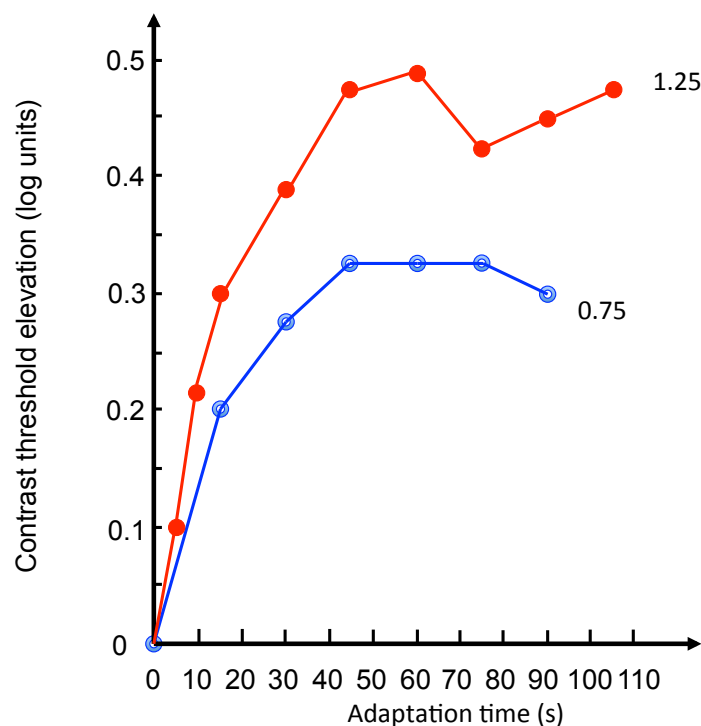
Figure 1.7: log contrast threshold elevation for one observer for a 15cdeg^{-1} adaptor target presented at 1.25 and 0.75 log units above threshold. Adaptor and test gratings were of the same spatial frequency and orientation. (Adapted from Blakemore & Campbell, 1969).

De Valois (1977) and Suter, Armstrong, Suter and Powers (1991) showed that in addition to a loss of contrast sensitivity at the adapting spatial frequency, contrast sensitivity was actually enhanced for neighbouring spatial frequencies, most prominently so for those

spatial frequencies 2.75-3.00 octaves away (Wilson & Regan, 1984) as illustrated in Figure 1.8.
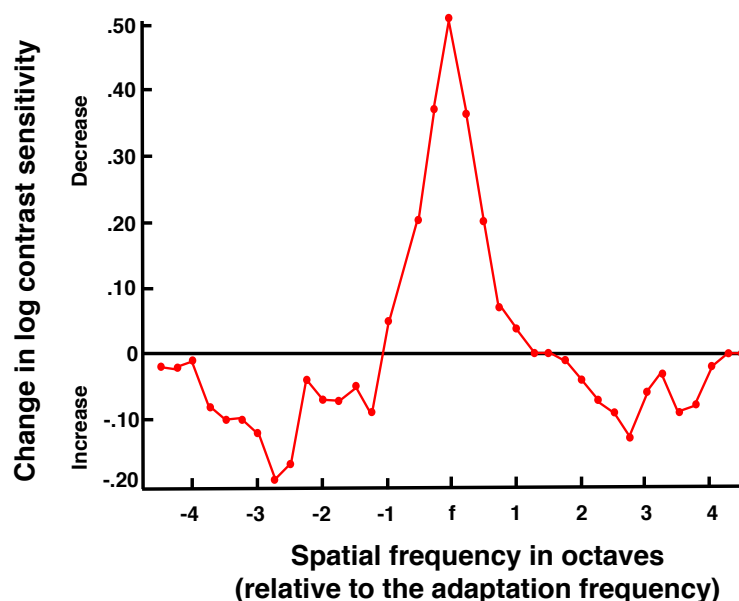
Figure 1.8: Change in contrast sensitivity as a function of spatial frequency in octaves relative to the adaptation frequency. Consistent with earlier literature, the greatest reduction in contrast sensitivity is centred at the adapting spatial frequency whilst facilitating of contrast sensitivity is highlighted at neigbouring frequencies. Reproduced from De Valois (1977), data from 59 subjects and normalised for spatial frequency.

1.5.6 Functional role of contrast adaptation

Contrast adaptation is thought to occur to maintain contrast constancy, *viz*., limiting the perception of stimulus blur and facilitating responses to changes in stimulus contrast (Georgeson & Sullivan, 1975; Greenlee & Heitger, 1988). The visual system is understood to adapt its sensitivity to the current range of light intensity in the environment. Adaptable and non-adaptable mechanisms allow the retina to discern between defocus and low contrast for emmetropisation control (Heinrich & Bach, 2002a). Contrast adaptation is different at retinal (measured using Pattern Electroretinogram, PERG) and cortical (measuring using Visual Evoked Potential, VEP) levels (Heinrich & Bach, 2002b). A reduction occurs in the firing rate of cortical neurons in V1 (Hammond, Mouat & Smith, 1985; Albrecht, Farrar & Hamilton, 1984; Movshon & Lennie, 1979). By utilising fMRI in human observers, Gardener et al. (2005) demonstrated that this decrease in neural response serves to shift contrast sensitivity such that the visual system recalibrates to optimise detection of the contrasts in the scene being viewed, whilst reducing sensitivity to uninformative features of the visual diet. Contrast adaptation allocates perceptual resources to optimise our sensitivity to match salient parts of visual scenes (Pestilli, Viera & Carrasco, 2007).

Contrast adaptation occurs both over a brief time scale (e.g. visual acuity enhancements after 30 min: Mon-Williams, Tresilian, Strang, Kochar & Wann, 1998) and over years (e.g.

changes brought about by cataracts and their removal: Fine, Smallman, Doyle & MacLeod, 2002).

1.6 Accommodation

Accommodation is the ability of the eye to alter its power to maintain a clearly focused image of an object on the retina even when the object's distance from the eye is reduced. It is a contrast maximising closed loop negative feedback system whereby the eye maximises or optimises the luminance contrast of the retinal image (Kruger et al., 2000). The Autonomic Nervous System (ANS) is responsible for initiating the accommodative response whereby the parasympathetic nervous system controls the far to near response (positive accommodation) whilst the sympathetic nervous system is responsible for near to far (negative) accommodation (McBrien & Millodot, 1986).

In an emmetropic eye, light rays from a point object 6m or further away will be parallel upon reaching the eye and will therefore be focused on the retina. If the object is moved closer to the eye, the light rays would then fall behind the retina making it appear blurred, and so the eye accommodates to bring the image into focus on the retina. Upon detection at the retina, a blur signal is transmitted through the magnocellular level of the Lateral Geniculate Nucleus (LGN) to the visual cortex and then on to the midbrain (oculomotor nucleus and the Edinger-Westphal nucleus) where a motor response is initiated. This response is transmitted as parasympathetic signals carried by the ciliary muscle via the oculomotor nerve, ciliary ganglion and short ciliary nerves causing relaxation of the anterior lens zonules. This increases the lens surface curvature and central thickness thereby increasing the optical power of the lens to reduce retinal defocus.

1.6.1 Components of accommodation

The process of accommodation is assumed to have four components: vergence, proximal, reflex and tonic (Table 1.3).

Component	Description
Vergence	Initiated by the disparity of the retinal images between the two eyes to bring together the visual axes of the eyes for near objects.
Proximal	Induced by the awareness of a near object
Reflex	Adjustment of the eyes refractive state in response to blur with the aim of reducing blur. It may be initiated when the eye changes fixation from far to near or by convergence.
Tonic	Passive state of accommodation of the eye in the absence of stimulus and thus corresponds to position of equilibrium of the sympathetic and parasympathetic nervous systems. It is found even in the absence of blur, proximal, and vergence cues.

Table 1.3 Components of an accommodation response.

1.6.2 Accommodation model

Defocus blur is the primary stimulus to initiate an accommodation response (Fincham, 1951; Campbell & Westheimer, 1960; Phillips & Stark, 1977; Tucker & Charman, 1979; Kruger & Pola, 1986; Kruger & Pola, 1987; Ciuffreda, 1991). Figure 1.9 illustrates the standard model of accommodation control that was first described by Hung and Semmlow (1980) and then modified by Jiang (1997). It presents a dual feedback mechanism of static accommodation control showing how the accommodation response is primarily initiated in response to defocus blur and this serves to maintain a clear retinal image. The Accommodative Stimulus (AS) forms a blur signal and this results in an Accommodative Response (AR). Accommodative Error (AE) is the difference between AR and AS and is the system input. Accommodative Sensory Gain control (ASG) represents the signal degradation that occurs in the sensory part of the system. The threshold for oculomotor control is represented by the Depth of Focus/Dead Space (DSP). The resulting signal then goes into the accommodative controller, a linear operator with gain, the Accommodative Controller Gain (ACG). Output from here is then summed with Vergence Accommodation (CA) and Tonic Accommodation (ABIAS).
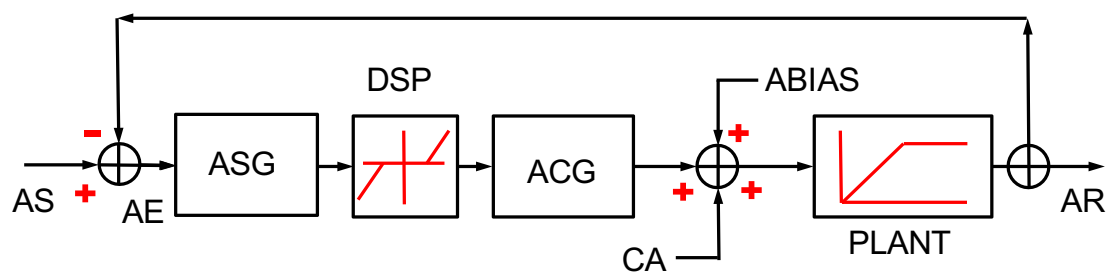
Figure 1.9: Reproduced from Jiang (1997) illustrating a model of accommodation control.

Measures of accommodation and their relation to myopia development

1.6.3 Amplitude of accommodation

In Rosenfield (1998), amplitude of accommodation is defined as the dioptric distance between the far-point and the near-point conjugate with the retina when accommodation has been fully exerted. Comparing amplitude of accommodation between myopic and emmetropic observers has produced conflicting results: Maddock, Millodot, Leat and Johnson (1981) and McBrien and Millodot (1986) found higher amplitude of accommodation in myopes; Fong (1997) reported lower amplitudes in myopes; Gawron (1981) and Fisher, Ciuffreda and Levine (1987) found no difference between refractive error groups. It has thus been concluded that amplitude of accommodation is an unlikely causal factor for myopia development. Furthermore, hypermetropic children have to accommodate more than myopic children but of course do not tend to become myopic (Wildsoet & Wallman, 1995).

1.6.4 Tonic accommodation

The level of tonic accommodation (see Table 1.3 above) as a function of refractive error has been investigated but with no consistent agreed outcome: the most frequent finding is that tonic accommodation is lower in myopia (Gwiazda, Bauer, Thorn & Held, 1995b; Chen, Schmid & Brown, 2003). However, two longitudinal studies have suggested lower tonic accommodation as a consequence of myopia rather than a precursor of myopia development (Yap, Garner, Kinnear & Frith, 2000; Zadnik et al., 1999) and thus concluded that tonic accommodation is not a suitable indicator of future myopia development.

1.6.5 Accommodative accuracy (lag and lead)

Accommodative lag results when the accommodative response is less than the accommodative stimulus. Figure 1.10 shows an Accommodative Stimulus-Response (ASR) function and illustrates over-accommodation (accommodative lead) at distance (where accommodative stimulus is 0D for an observer corrected for distance viewing), but progressive under accommodation with increasing accommodative demand (accommodative lag).
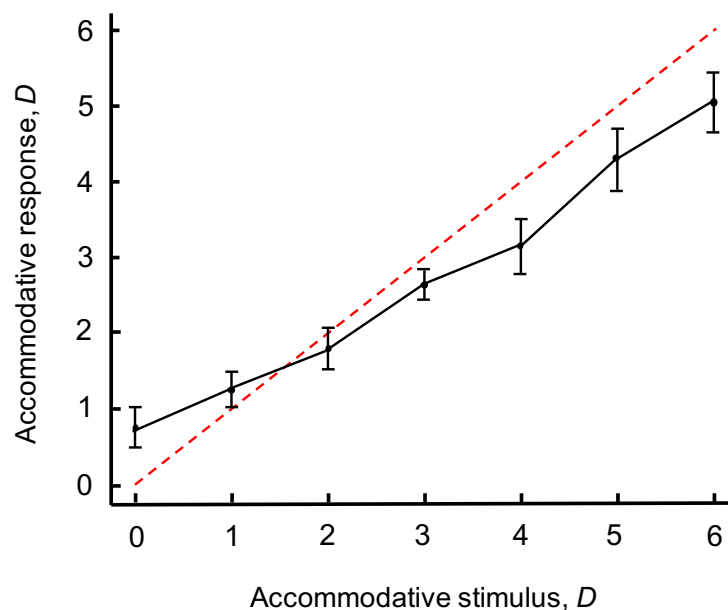
Figure 1.10: Plot of averaged accommodative stimulus-response (ASR) data from 10 visually normal subjects. Data points and error bars represent group mean ± SEM (adapted from Ong, Ciuffreda & Tannen, 1993). Dotted red line represents 1:1 stimulus/response line.

Thus, during near work (where there will be a relatively large accommodative demand) the lag of accommodation could result in hypermetropic blur (Figure 1.11).
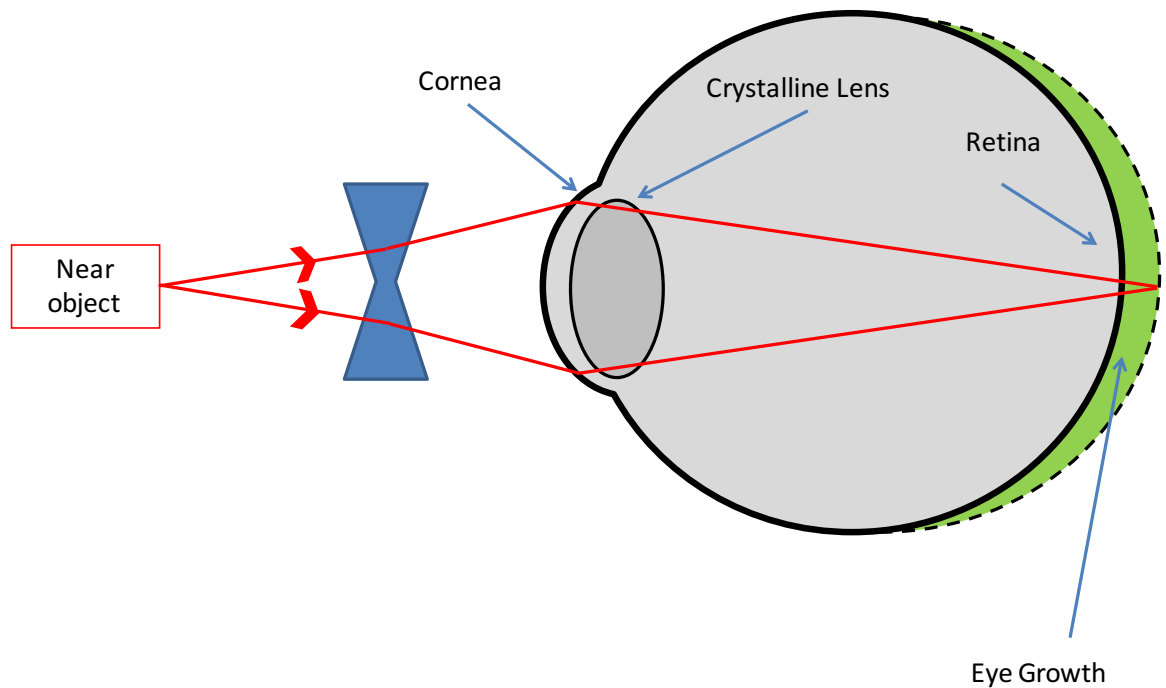
Figure 1.11: Accommodative lag: accommodation response is less than the accommodative demand for the near object placed in front of this myope who has been corrected for distance vision, resulting in hyperopic defocus.

It has been proposed that individuals with a greater lag of accommodation who undertake excessive near work may develop myopia due to hypermetropic retinal defocus, which is thought to provide a stimulus for axial elongation (Goss & Wickham, 1995; Zadnik & Mutti, 1995; Grosvenor & Goss, 1999).

Differences in accommodative lag between emmetropes and myopes have been equivocal: McBrien and Millodot (1986) found that Late Onset Myopes (LOM: onset 15 years or later) accommodate less for near targets when compared to Early Onset Myopes (EOM: onset 13 years or earlier); EOM children had significantly larger accommodative lags than emmetropic children in a study by Gwiazda et al. (1993b); Abbott et al. (1998) replicated the work of Gwiazda et al. (1993b) but found no significant difference in the accommodative response made by emmetropes, EOM and LOM; Yeo, Kang and Tang (2006) found progressing myopes to have higher accommodative lags for higher accommodation demands than non-progressing myopes and emmetropes; Allen and O'Leary (2006) showed that myopia progression was highly correlated with greater accommodative lag although their results don't differentiate between their emmetropic, EOM and LOM participants; Weizhong et al. (2008) and Bernsten et al. (2011) found that myopia progression in myopic children was not significantly correlated with accommodative lag in children.

Accommodative lag has also been proposed as a consequence (as opposed to cause) of myopia development (Mutti et al., 2006). Nakatsuka, Hasebe, Nonaka and Ohtsuki (2003) found no significant difference in accommodative lag between early onset myopic and emmetropic adults. They measured accommodative lag both under habitual viewing conditions (binocular measurement wearing spectacles or contact lenses) and under experimental conditions (monocular viewing after contact lens correction, Rosenfield & Gilmartin, 1998; Gwiazda et al., 1993b; Abbott et al., 1998) and found significantly greater lag in the monocular condition.

Various previous studies have used lenses that incorporate a reading addition, typically progressive add lenses (PALs) to relax the accommodative demand/eliminate accommodative lag (reviewed by Walline, 2016). In two randomised, masked studies of PALs, the fastest mean progression of myopia occurred in those with higher accommodative lag (Gwiazda et al., 2004; Hasebe et al., 2008), although they had limited efficacy at slowing myopia progression. In adults with stable myopia, the mean lag has been shown to be the same as that of adult emmetropes (Abbot et al., 1998, Nakatsuka et al., 2003, Seidemann & Schaeffel, 2003; Harb et al., 2006). How retinal defocus as a result of a lag of accommodation is converted into axial elongation which involves modification to the sclera is less certain (Schmid & Strang, 2015).

More informative findings come from studies which have consistently shown accommodative variability in myopes: Seidel, Gray and Heron (2003) and Seidel, Gray and Heron (2005) found no difference in accommodative lag between emmetropes and myopes but suggested that larger accommodative microfluctuations in myopes implied larger accommodative variability; Radhakrishnan, Allen and Charman (2007) also found no difference in lag between the two refractive error groups but found that myopes have a slower velocity of accommodation; finally Langaas et al. (2008) found no difference in lag between refractive error groups in children and suggested that myopes have more variable accommodation.

1.6.6 Accommodative microfluctuations

Accommodative microfluctuations are small variations in dioptric power (within an envelope of about 0.50D) of the crystalline lens (Campbell, Robson & Westheimer, 1959; Denieul, 1982; Kotulak & Schor, 1986a; Charman & Heron, 1988; Collins, Davis & Wood, 1995; Winn, Pugh, Gilmartin & Owens, 1990; Seidel et al., 2003). They provide feedback to ensure that the accommodation response is commensurate with the accommodative demand (Kotulak & Schor, 1986b; Winn et al., 1990; Gray, Winn & Gilmartin, 1993a; Charman & Heron, 2015) and provide directional cues of dynamic accommodation responses to

changes in target vergence (Campbell et al., 1959; Campbell & Westheimer, 1960; Gray, Winn & Gilmartin, 1993b). The magnitude of microfluctuations is influenced by pupil size (Campbell et al., 1959; Campbell & Westheimer, 1960; Gray et al.,1993b; Stark & Atchison, 1997, Charman & Radhakrishnan, 2009), target luminance (Alpern, 1958; Schor, Johnson & Post, 1984; Gray et al., 1993b), spatial frequency content of the stimulus (Bour, 1981; Niwa & Tokoro, 1998; Day, Gray, Seidel & Strang, 2009), and the stimulus vergence demand (Krueger, 1978; Usui & Stark, 1977, Denieul, 1982; Kotulak & Schor, 1986a; Heron & Schor, 1995; Stark & Atchison, 1997; Day, Strang, Seidel, Gray & Mallen, 2006).

Seidel et al. (2003), Day et al. (2006), Harb et al. (2006) and Langaas et al. (2008) all reported larger accommodative microfluctuations in myopes than emmetropes, implying that myopes may be less able to rectify small errors of hypermetropic retinal blur when compared with emmetropes.

1.6.7 Near work induced transient myopia or accommodative adaptation

Near work induced transient myopia (NITM) refers to the shift in distance refractive error following a prolonged near visual task (Ong & Ciuffreda, 1995). Under closed loop conditions, pre-task, near task and post task accommodation measurements are obtained in lighted conditions *after* an initial period of dark adaptation. Thus, normal blur-driven feedback mechanisms are present (Rosenfield, 1998), and this process can result in accommodative adaptation (Ebenholtz, 1983; Ehrlich, 1987; Ciuffreda & Ordonez, 1995; Gwiazda et al., 1995a; Ong & Ciuffreda, 1995). This is in comparison to open loop measures of accommodative hysteresis, wherein pre- and post-task measurements are acquired in total darkness.

The magnitude and duration of NITM is greater in myopes (particularly LOM) compared to other refractive error groups (Ciuffreda & Wallis, 1998; Ciuffreda & Lee, 2002; Vasudevan & Ciuffreda, 2008; Arunthavaraja, Vasudevan & Ciuffreda, 2010; Sivaraman et al., 2015). Furthermore, progressing myopes are more likely to exhibit NITM than myopes with stable refractive error (Vera-Diaz, Strang & Winn, 2002, Wolffsohn et al., 2003; Vasudevan & Ciuffreda, 2008). NITM has been reported to range from 0.12 to 1.30D with a mean value of 0.40D (Vasudevan & Ciuffreda, 2008). NITM creates transient myopic defocus that has been postulated as a possible cause of myopia in humans (Ong, Ciuffreda & Rosenfield, 1995; Vera-Diaz, Strang & Winn, 2000; Wolffsohn et al., 2003; Ciuffreda & Vasudevan, 2008).

Previous studies have shown that imposing myopic defocus by slightly under-correcting myopia in humans results in further myopia progression (Chung, Mohidin & O'Leary, 2002; Adler & Millodot, 2006; Vasudevan, Esposito, Peterson, Coronado & Ciuffreda, 2014).

Wolffsohn et al. (2016) administered a questionnaire to eye care practitioners globally, the findings of which concluded that under-correction of myopia was thought to be the least effective management strategy for myopia control. Interestingly, Li et al. (2015) found that over a period of one year, accommodative lag significantly decreased with increasing undercorrection of myopia in 12 year old Chinese school children. Conversely, Goss (1984) overcorrected 36 myopes by -0.75D and found no difference in rates of myopia progression between the treatment and control group.

It appears that retinal defocus induced with positive and negative lenses can alter the emmetropisation process, implying that mechanisms exist to detect and compensate for the imposed defocus (reviewed in Goss & Wickham, 1995; Wildsoet, 1997). Hung and Ciuffreda (2007) proposed an incremental retinal-defocus theory (IRDT) whereby a time-averaged decrease in retinal-image defocus area decreases the rate of the release of retinal neuromodulators which results in decreased scleral structural integrity. This increases the rate of scleral growth and in turn the eye's axial length which leads to myopia.

Long distance viewing has been reported to reduce myopic progression in children (Rose, et al., 2008a). Onal et al. (2007) suggested it can be protective against myopia development in younger years. Furthermore, periods of distance viewing may help dissipate the effects of NITM (Ciuffreda & Vasudevan, 2008): conversely, persistent near work may prolong NITM, providing greater exposure to retinal defocus and thus promoting myopia development in susceptible individuals (Ong, Ciuffreda & Rosenfield, 1995).

1.7 Spatial frequency and accommodation
The accuracy of steady state accommodation for high contrast sinusoidal gratings was found to be optimal for spatial frequencies 3-5cdeg^{-1} (Owens, 1980). Ward (1987) also elicited the best accommodation response for sinusoidal gratings of 5cdeg^{-1} as opposed to 1.67cdeg^{-1} and 15cdeg^{-1}. Strang et al. (2011) showed an improved percentage of correct step responses to 4cdeg^{-1} gratings as opposed to 16cdeg^{-1}. Taylor, Charman, O'Donnell and Radhakrishnan (2009) showed similar mean static accommodation behaviour in emmetropes and myopes for Gabor targets of 1,4,8 and 16cdeg^{-1}. However, microfluctuation is considered important and a lack of dynamic measurement meant that microfluctuation measurement was not incorporated in their study. Day et al. (2009) measured accommodative microfluctuations in myopes and emmetropes in response to the presentation of sine wave gratings for spatial frequencies 0.5,1,2,4,8, and 16cdeg^{-1}. For all participants, microfluctuations were smallest for the 2cdeg^{-1} and 4cdeg^{-1} targets and increased in magnitude when viewing the 0.5cdeg^{-1} and 16cdeg^{-1} targets. Emmetropes had significantly larger microfluctuations at 0.5cdeg^{-1} compared with 2,4,8cdeg^{-1} whilst myopic participants' microfluctuations were significantly larger at 16cdeg^{-1} compared to 4cdeg^{-1}.

Comparing the increase in microfluctuations between the 4cdeg^{-1} and 16cdeg^{-1} targets and between refractive error groups, myopes had a significantly larger increase than emmetropes.

Radhakrishnan, Hartwig, Charman and Llorente (2015) compared accommodative responses to single Chinese and Latin characters. Their myopic and emmetropic Chinese illiterate pre-presbyopic participants showed no significant differences between their monocular accommodative responses to Chinese characters (stroke frequency 2.4cdeg^{-1}) or Latin characters (1.5cdeg^{-1}). 2-D Fourier spectra of the comparatively more complex Chinese characters showed only weak evidence for strong periodicity at any particular frequency or orientation whilst the Latin characters showed strong fundamental and harmonic frequency components at specific orientations.

1.8 Contrast adaptation and myopia

Reading text at near may lead to contrast adaptation (Greenhouse, Bailey, Howarth & Berman, 1992; Chen, Brown & Schmid, 2006). It entails the prolonged viewing of a high-contrast stimulus class that contains a repetitive pattern in which a restricted range of spatial frequencies and orientations are found (Wallman & Winawer, 2004). The repetitive patterns in printed text yield a spatial frequency distribution that is quite unlike that found in natural images, which possess a 1/f amplitude spectrum, with diminishing power at higher frequencies (Field, 1987; Tolhurst, Tadmor & Chao, 1992; Webster & Mollon, 1997). Majaj, Pelli, Kurshan & Palomares, (2002) suggested that the spatial frequency created by text strokes is an excellent predictor of the centre frequency observers use for letter identification. Hence, it is reasonable to surmise that reading text will produce contrast adaptation that alters subsequent spatial frequency sensitivity, when compared to a more naturalistic visual diet.

Contrast adaptation following prolonged viewing of text on a computer screen has been investigated previously by Lunn and Banks (1986), Greenhouse et al. (1992) and Magnussen, Dyrnes, Greenlee, Nordby and Watten (1992). Although not specifically concerned with the influence of contrast adaptation and myopia, their findings are noteworthy in that they all found the greatest magnitude of contrast adaptation at the fundamental spatial frequencies of the text targets.

More recently, adaptation to printed text was explored in myopic and emmetropic children (Yeo, Atchison, Lai & Schmid, 2012). Lower contrast adaptation was noted after text viewing when compared to 2-D sinusoidal stimuli in all participants, and a greater magnitude of adaptation was elicited in myopic children across all frequencies (Yeo et al., 2012). However, adaptation effects were relatively small, and were not shown to be specific to the

row or text stroke frequency. While consistent with contrast adaptation during reading, the lack of specificity, a hallmark of adaptation, leaves open the possibility that other processes could have been involved.

Due to the reductions in neural firing (see section 1.5.4) and contrast sensitivity, and the consequent desensitisation of the visual system (as a function of its own activity), contrast adaptation has been described in terms of visual fatigue (Georgeson & Harris, 1984) and neural fatigue (Goldstein, 2007). Diether, Wallman and Schaeffel (1997) suggested the reduced neural activity implied reduced retinal activity: given that a good quality visual signal consisting of a variety of spatial frequencies, supra-threshold contrast and high retinal activity is critical for normal ocular development (Bartmann & Schaeffel, 1994; Napper et al., 1997; Schmid, Brinkworth, Wallace & Hess, 2006), contrast adaptation may have bearing on the emmetropisation process.

1.9 Accommodation, contrast adaptation and myopia

Evidence from animal models (section 1.4.1) show that hypermetropic defocus produces myopia. Indeed, small but significant increases in axial length in humans have been shown in response to 60 minutes hypermetropic defocus (Read, Collins & Sander, 2010). This compounded with evidence of increasing myopia prevalence associated with increasing levels of education and intensive schooling and near-work (section 1.3.2) provides strong evidence in support of the hypothesis that the accommodation system is involved in the development of myopia, given that hypermetropic defocus may result from a lag of accommodative response during reading. Day and Duffy (2011) suggest that the progression and/or development of myopia could be related to the type of defocus, the duration of exposure, the magnitude of defocus, and the sensitivity to such defocus blur. Manipulation of contrast sensitivity as a consequence of contrast adaptation may have the potential to alter the accommodative response and act as an accompanying cue for myopigenesis.

Animal models suggest against the actual process of accommodation as being myopigenic as lens induced myopia still developed in animals where the Edinger-Westphal nucleus was ablated (Schaeffel, Trolio, Wallman & Howland, 1990) or ciliary nerve severed (Schmid & Wildsoet, 1996). The role of retinal image quality in driving ocular growth in the development of myopia has been demonstrated in animals, leading to increased interest in the factors that affect retinal image quality in humans (Smith & Hung, 1999; Wallman & Winawer, 2004). Animal models have shown that sharp, high fidelity stimuli comprising a variety of spatial frequencies (Bartmann & Schaeffel, 1994) presented at supra-threshold contrast (Schmid et al., 2006) are critical for normal ocular development. A degraded retinal image,

as a consequence of contrast adaptation (which will contain sub-threshold contrast), may therefore lead to perceptual blur.

Myopes have been shown to have higher blur tolerance than emmetropes (Rosenfield & Abraham-Cohen, 1999; George & Rosenfield, 2004). Under cycloplegia (thereby eliminating any accommodation response), defocus induced with negative lenses caused a greater reduction in visual acuity (Radhakrishnan, Pardhan, Calver & O'Leary, 2004a) and contrast sensitivity for spatial frequencies between 1-8cdeg^{-1} (Radhakrishnan, Pardhan, Calver & O'Leary, 2004b) in non-myopes than myopes. Myopes showed a greater reduction in contrast sensitivity for positive compared to negative defocus and the optimum focus for intermediate spatial frequencies was more myopic in myopes than non-myopes (Radhakrishnan et al., 2004b). The reduction in visual acuity was not significantly different between refractive groups for positive lenses (Radhakrishnan et al., 2004a). Section 1.7 identifies intermediate spatial frequencies in driving an optimal accommodation response and the reduced accommodative response reported in some myopes (section 1.6.5) may be caused by the more negative optimal focus for these frequencies.

Investigating blur sensitivity after blur adaptation has yielded conflicting results: Cufflin, Mankowska and Mallen, (2007) found reduced sensitivity whilst Wang, Ciuffreda and Vasudevan, (2006) found increased blur sensitivity after blur adaptation. Comparing refractive error groups, Rosenfield and Abraham-Cohen (1999) used cycloplegia in adult subjects to measure subjective perception of blur and found that myopes were less sensitive to blur than emmetropes. Conversely, Schmid, Iskander, Li, Edwards and Lew (2002) found no correlation between blur thresholds and refractive error magnitude in children, although they did find that blur detection ability was more variable in myopic children. Target characteristics including size and spatial frequency may also have bearing on detectability which might account for differences found in either of these studies. Brief exposure to image blur has been shown to improve visual acuity (Pesudovs & Brennan, 1993; Mon-Williams et al., 1998; George & Rosenfield, 2004). It is unknown as to whether the blur deficits in myopes are a cause or consequence of myopia.

Vera-Diaz, Gwiazda, Thorn and Held (2004) showed increased near accommodation responses in myopes, but not emmetropes, after three minutes of blur exposure. Adaptation to natural scenes viewed through defocus blur has been shown to increase supra-threshold contrast sensitivity at 3.22cdeg^{-1} (Ohlendorf & Schaeffel, 2009), between 3-4cdeg^{-1} (Venkataraman, Winter, Unsbo & Lundström, 2015) and at 8cdeg^{-1} and 12cdeg^{-1} (Rajeev & Metha, 2010). However, extant studies that have investigated the effect of blur adaptation on contrast sensitivity have not examined the influence of different refractive groups. It is

worth highlighting that refractive error was unchanged in all these studies and this is strongly indicative of a perceptual basis to the adaptation.

As discussed above (section 1.6.2), defocus blur is considered the primary stimulus for the initiation of the accommodation response and animal studies show that the eye responds preferentially to no blur (Norton, Siegwart & Amedo, 2006; Kee et al., 2007). It has been hypothesised that myopic observers may have reduced ability to perceive blur or that their neural accommodative response to blur may be poorer (Gwiazda et al., 1995b). Measuring ASR to positive and negative lenses facilitates understanding of the neural accommodative response before blur is perceived. Gwiazda et al. (1993b) found that myopic children showed reduced accommodative responses when viewing through negative lenses compared with emmetropes when presented with static blur stimuli. Later, Gwiazda et al. (1995a) found a positive correlation between the change in accommodative response and change in refractive error over a 6-12 month period in myopes but not emmetropes, re-enforcing the link between poor accommodation and myopia development. Jiang and White (1999) investigated accommodative adaptation in emmetropes and late-onset myopes after 20 minutes of playing an interactive computer game viewed through -4.00D lens at 50cm (6.00D accommodative demand). They found increased static accommodative responses post-adaptation but no difference between the two refractive groups.

Chronic blur adaptation due to uncorrected refractive error could alter sensitivity to retinal image defocus. Whilst imposed optical defocus may simulate the visual experience of an uncorrected myope, this does not explain the role of near work as a myopigenic stimulus prior to myopia onset.

1.10 Cognitive demand and accommodation

Van-Alphen (1961) stated that learning, as opposed to simply close work, is a complicated psycho-visual mechanism. The accommodative response under normal viewing conditions is determined by a complex and subtle interaction of optical and non-optical factors and the mental effort associated with the visual task can significantly alter it (Winn, Gilmartin, Mortimer & Edwards, 1991). Section 1.3.2 discusses higher myopia prevalence with increasingly competitive and rigorous education systems. Goldschmidt (1968) reported higher myopia prevalence in university students than clerical workers, for whom myopia prevalence was higher than fine craftsmen. These occupations would all typically involve persistent near tasks and this finding suggests the development of near-work induced myopia may not be solely related to the processes which determine retinal image quality, but may be related to the cognitive demand of the near work task.

It addition to the level of mental workload, other cognitive influences on accommodation response include the method of presentation of the information to be processed, the nature of the processing task and perceived distance (Edgar, 2007). Winn et al. (1991) found a differential effect on the accommodation response depending upon whether the mental processing task required information from a visual stimulus or a non-visual source (e.g. memory).

Studies have demonstrated that variation in cognitive demand may produce significant changes in the accommodative response; however, results to date are inconsistent. In some studies, the level of accommodation has been shown to decrease (Malmstrom, Randle, Bendix & Weber, 1980; Malmostrom & Randle, 1984; Birnbaum, 1984; Rosenfield & Ciuffreda, 1990) as a result of mental effort, whilst other studies have shown cognitive effort increases the accommodative response (Kruger 1980; Post, Johnson & Owens, 1985; Winn et al., 1991). Bullimore and Gilmartin (1988) showed increased accommodative response under cognitive demand conditions for a 1.00D stimulus and a reduced response for 5.00D stimulus and concluded that task distance can influence the direction of accommodative shift. However, comparison of refractive error group was not made in the aforementioned studies.

Comparing refractive groups, late onset myopes have been shown to have lower tonic accommodation than emmetropes under passive conditions but a cognitive counting task resulted in a positive shift in tonic accommodation that was significantly higher in the myopic cohort (Bullimore & Gilmartin, 1987). Wolffsohn, Gilmartin, Thomas and Mallen (2003) showed that for early onset myopes, the level of cognitive activity determined the persistence of NITM. Rosenfield and Ciuffreda (1994) found increased NITM after a 10 minute sustained near visual task at three levels of cognitive demand in visually normal subjects, however there was no significant difference between the three cognitive levels and effect of refractive error group was not examined.

Of further interest is the finding that inhibition of the sympathetic nervous system (which is responsible for near to far accommodation, section 1.6) and imposition of cognitive effort induced a mean increase in accommodation (Bullimore & Gilmartin, 1988). This is indicative of non-optical factors being responsible for cognitive induced changes in the accommodative response. Greater attention to a task may require more accurate accommodation (Bullimore & Gilmartin, 1988) and Berntsen et al. (2011) suggested that tasks with greater cognitive demand would be expected to slightly reduce the amount of accommodative lag measured. The role of cognitive effort has not previously been investigated in relation to the magnitude of contrast adaptation. There may be interaction between the role of optical factors, such as reduced retinal image quality, as a consequence

of contrast adaptation and non-optical factors, including the cognitive demand of the near visual task, in the initiation of an optimal accommodation response which, if sub-optimal, might act as a myopigenic stimulus.

1.11 Prior visual experience

Webster and Miyahara (1997) showed that contrast adaptation to the low frequency bias (1/*f*: see section 1.8) in a range of natural scenes selectively reduces low frequency contrast sensitivity but has little effect at higher frequencies. It was suggested that the common spatial structure of natural scenes may tend to maintain the visual system in a common state of spatial contrast adaptation, characterised by this reduced sensitivity at low to medium spatial frequencies (Webster, 1999). As discussed above (section 1.8), text contains a comparatively more restricted range of spatial frequencies and orientations, which may result in a quite different "common state" of contrast adaptation compared with a natural scene. The shape of the baseline contrast sensitivity function could therefore depend on an individual's prior visual experience (Webster, Werner & Field, 2005; Elliot, Hardy, Webster & Werner, 2007), and the true potential for adaptation may be masked. Co-incidentally, Li, Polat, Makous and Bavelier (2009) showed that playing action video games enhances the CSF, further indicative of the potential for prior visual experience to influence pre-adaptation contrast sensitivity.

1.12 Specific study aims

This review and discussion of extant literature has identified perceptual adaptations (contrast adaptation and accommodative inaccuracies) that may result from near work, specifically reading. The primary aim of this thesis is to better understand the role of these adaptations as potential mechanisms for inducing retinal image defocus that may give rise to retinal error signals that promote eye growth, and therefore myopia. Furthermore, the role of prior visual experience and cognitive effort will be explicitly examined in this research.

Figure 1.12 summarises the adaptation hypothesis that the experimental work in this thesis will explore.

Reading

↓

Prior visual experience → **Contrast adaptation** ← **Cognitive effort**

↓

Reduced retinal image quality

↓

Reduced blur perception

↓

Reduced accommodative response

↓

Hyperopic blur

↓

Stimulus to ocular growth
=
myopia
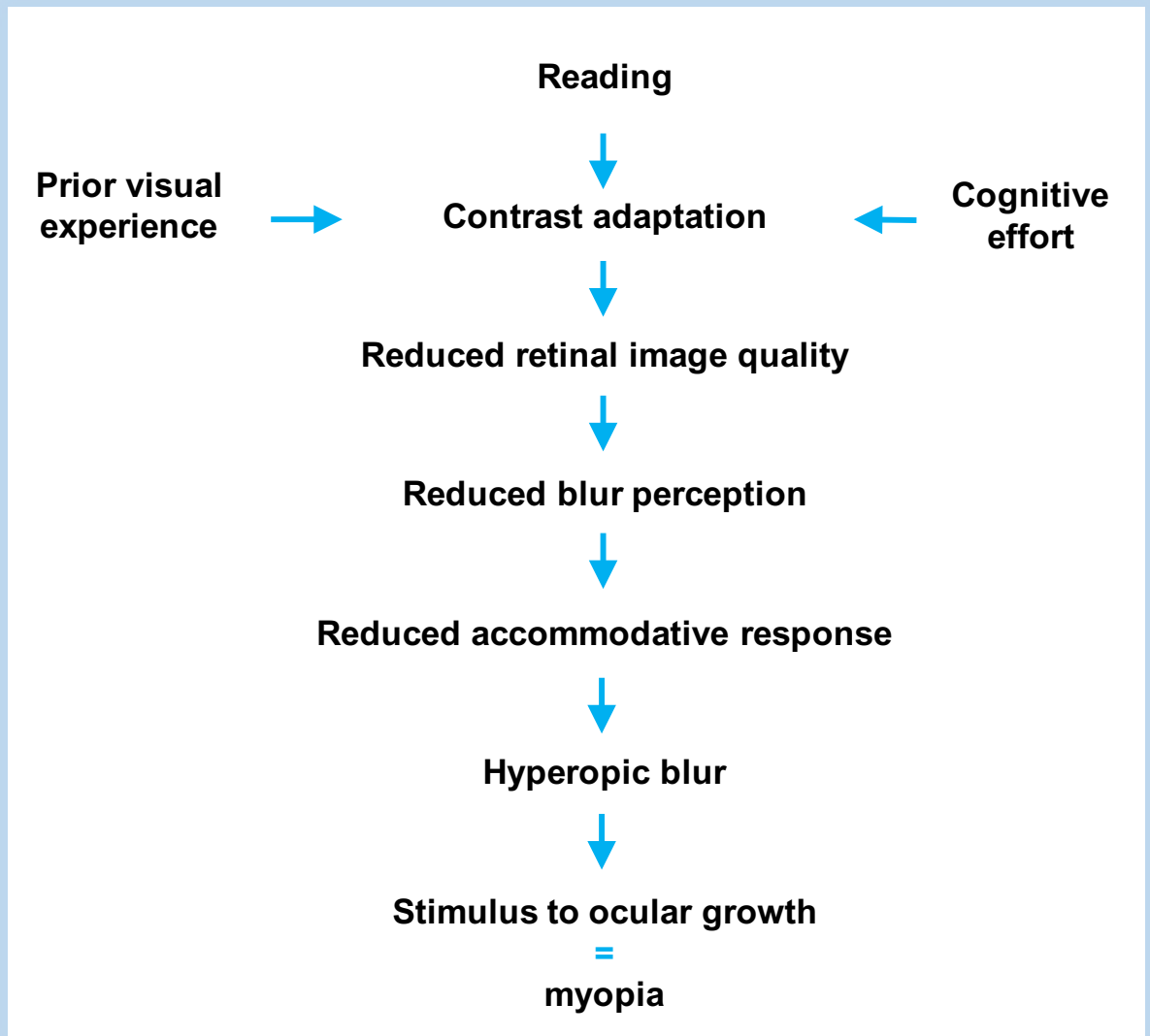
Figure 1.12: Summary of working hypothesis relating reading to myopia progression.

To better understand the role of contrast adaptation, accommodative accuracy, prior visual experience and cognitive effort as risk factors for myopia progression, experiments were designed in which contrast sensitivity and accommodation accuracy were measured after periods of adaptation in young adult emmetropic and myopic participants. All adaptive stimuli were viewed binocularly and in-focus (as corrected myopes would perceive them), rather than through optical defocus. This may be more informative in understanding the role of near work in myopia development.

The experimental work undertaken and presented in the subsequent chapters of this thesis is divided into four experiments:

1) Measurement of contrast sensitivity before and after adaptation to uniform white noise and text stimuli.

2) Measurement of contrast sensitivity before and after adaptation to a text stimulus with an improved experimental paradigm.

3) Measurement of contrast sensitivity before and after adaptation to a stimulus that matched the contrast, luminance and spatial frequency of the text stimulus in experiment 2, but with randomised phase, thereby making it incomprehensible (to manipulate cognitive demand).

4) Measurement of accommodative accuracy before and after adaptation to the text and phase-randomised text stimuli.

The specific aims of each experiment and the research questions explored are presented below:

Experiment 1:

Prior visual experience (section 1.11) has not been accounted for in previous measures of contrast adaptation, and was investigated after adaptation to a uniform white noise stimulus. Yeo et al. (2012) suggested myopic children experience greater contrast adaptation (section 1.8) after reading printed text; however, this wasn't at the dominant frequencies derived from the text stimulus as was shown by Lunn and Banks, (1986), Magnussen et al. (1992) and Greenhouse et al. (1992). This experiment examines the following questions:

- Does uniform white noise induce contrast adaptation, and is it an appropriate surrogate to make pre-adaptation contrast sensitivity more comparable between participants?
- Does reading text on a screen induce contrast adaptation?
- Which spatial frequencies display contrast adaptation?
- Is there a difference in the magnitude of contrast adaptation between young adult myopic and emmetropic observers?

Experiment 2:

The results of Experiment 1 were inconsistent with earlier studies that measured contrast adaptation after reading. A revised experimental paradigm was designed to measure contrast adaptation in young adult participants to answer the following questions:

- Does reading text on a screen induce contrast adaptation?
- Which spatial frequencies display contrast adaptation?
- Is there a difference in the magnitude of contrast adaptation between young adult myopic and emmetropic observers?

Experiment 3:

It is unclear whether the adaptation effects that follow reading are caused by the restricted range of spatial frequencies and orientations in text, or are also contributed to by the high-order processes and sustained cognitive effort required in active reading. Contrast adaptation was measured after adaptation to a phase-randomised stimulus to investigate the role of either cognitive effort or stimulus phase in eliciting a contrast adaptation response.

- Does stimulus phase influence contrast adaptation?
- Which spatial frequencies display contrast adaptation?
- Is there a difference between refractive error groups?
- Is altering stimulus phase an appropriate surrogate for investigating cognitive effort?

Experiment 4:

Differences in the accuracy of accommodation response have been shown between refractive error groups and cohorts of varying refractive error stability but has not previously been compared before and after reading. This studied was designed to investigate whether reading and adaptation to the phase randomised stimulus altered accommodative accuracy. The experiment sought to examine:

- Is there a difference in accommodative lag between refractive error groups?
- Is there a difference in accommodative lag before and after reading, concurrent with contrast adaptation in experiment 2?
- Cognitive effort influences accommodative accuracy (section 1.10): can a change in accommodative lag help differentiate the role of either cognition or stimulus phase in inducing contrast adaptation?

1.13 Summary of Contribution to Knowledge

The results presented in this thesis show for the first time that reading text on a screen induces contrast adaptation in young adult emmetropes and myopes: the effect was specific to the spatial frequency created by rows of text and inter-text space and myopes incurred more than twice the adaptation of emmetropes. It was also revealed that accommodative lag increased significantly after reading for myopes but not emmetropes. There was no significant contrast adaptation or change in accommodative accuracy for either participant group after adaptation to the incomprehensible phase randomised stimulus. Thus, myopes were shown to be more susceptible to adaptation to the specific spatial frequency and statistical characteristics of text as a consequence of active reading. These findings make

a new and pertinent contribution to understanding how near-work and specifically reading might influence the development of myopia.

1.14 Outline Structure of Thesis

An outline of the subsequent chapters of this thesis is as follows:

Chapter 2. Experiment 1

Chapter 3. Experiment 2

Chapter 4. Experiment 3

Chapter 5. Experiment 4

Chapter 6. Summary and conclusions

Chapter 2

Experiment 1: Contrast adaptation to uniform white noise and text stimuli.

2.1 Introduction

Near work is frequently cited as being myopigenic (Saw et al., 2001; Mutti et al., 2002; Saw et al, 2002), even though the exact mechanism that mediates this relationship is uncertain. The most common type of near work is reading. Reading involves prolonged viewing of a high-contrast stimulus with a repetitive pattern that contains a restricted range of spatial frequencies and orientations (Wallman & Winawer, 2004) which may lead to contrast adaptation (Greenhouse et al., 1992; Chen et al., 2006). Animal models have shown that sharp, high fidelity stimuli comprising a variety of spatial frequencies (Bartmann & Schaeffel, 1994) presented at supra-threshold contrast (Schmid et al., 2006) are critical for normal ocular development. A degraded retinal image, as a consequence of contrast adaptation (which will contain sub-threshold contrast), may therefore lead to perceptual blur, which in turn may lead to hypermetropic retinal defocus and ultimately act as a stimulus to myopia development.

The repetitive patterns in printed text yield a spatial frequency distribution that is quite unlike that found in natural images: natural images possess a $1/f$ amplitude spectrum, with diminishing power at higher frequencies (Field, 1987; Tolhurst et al., 1992; Webster & Mollon, 1997); conversely, the amplitude spectrum of text is narrow (Solomon & Pelli, 1994) and is purported to contain peaks that correspond to the row frequency and character stroke frequency (Majaj et al., 2002). Hence, it is reasonable to surmise that reading text will produce contrast adaptation that alters subsequent spatial frequency sensitivity, relative to a more naturalistic visual diet.

If reading text does induce contrast adaptation, then the magnitude of adaptation after reading would be dependent on participants' prior visual experience. This has not been considered in previous measures of contrast adaptation as reviewed in section 1.11. An individual who spends more time outdoors may habitually be adapted to the low frequency bias (1/f) of a natural scene (Webster, 1999) as opposed to adaptation to a more specific range of frequencies and orientations that may result from near work such as reading (Wallman & Winnawer, 2004).

Uniform white noise contains constant spectral density across a range of spatial frequencies. Given the randomised nature of the unbiased spatial frequency distribution in a stimulus of white noise, it was hypothesised that adapting participants to such a stimulus at the start of an experiment would make baseline contrast sensitivity more comparable across participants prior to text adaptation, irrespective of their prior visual experience.

In this study, contrast adaptation was investigated in myopic and emmetropic participants following 30 min of adaptation to a uniform white noise stimulus and then after 30 min of reading on-screen text. Contrast sensitivity for selected spatial frequencies was measured, including those corresponding to the horizontal text rows (text row frequency) and to the character strokes (text stroke frequency), to ascertain whether reading altered sensitivity specifically to these spatial frequencies.

Figure 1.12 summarises the hypothesis that reading text would induce contrast adaptation, which in animal models has been found to cause myopia (Diether, Gekeler & Schaeffel, 2001). Specifically, for this experiment, the hypothesis was that myopic participants would exhibit a greater magnitude of adaptation after reading text, compared with emmetropic participants.

2.2 Method
2.2.1 Participants
Twenty young adult participants took part, aged 19 to 34 years (mean age 21.9 ± 3.37), 10 of whom were classified as myopic (spherical equivalent refraction, sphere + ½ cylinder [SER]) (SER > -0.75D) and 10 emmetropic (SER +0.50 to -0.25D), summarised in Table 2.1. Refractive error was determined initially by retinoscopy, and then subjective refraction was undertaken at a standard testing distance of 6m using the endpoint criterion of maximum plus consistent with best visual acuity (best sphere) and cross-cylinder techniques. Visual acuity was measured on a conventional backlit Snellen chart.

Inclusion criteria were: best-corrected acuity ≤ 6/6 in each eye; monocular Pelli-Robson Chart log contrast sensitivity ≥ 1.65, spherical equivalent refraction (SER) ≤ -5.00DS SER ≤ +0.50DS; astigmatism ≤0.75DC, anisometropia ≤ 1.00D, an absence of any ocular pathology.

	Emmetropes	Myopes
Mean age (y) ± SD	20.3 ± 0.78	23.5 ± 4.13
Gender (male:female)	5:5	9:1
Mean SER ± SD (D)	0.08 ± 0.11	-2.95 ± 1.52

Table 2.1: mean age, gender and mean spherical equivalent refractive error (SER) for emmetropic and myopic participants.

Participants who fulfilled the inclusion criteria were given a verbal explanation of the procedures and a written information sheet (Appendix A). Informed written consent (Appendix B) was obtained from all participants, and they were advised of their right to withdraw at any time. The research was approved by the University Ethics Panel and

followed the tenets of the Declaration of Helsinki. Data were collected from all participants in one session.

2.2.2 Apparatus

2.2.2.1 Room illumination

The room illumination was measured using a CEM DT1308 light meter (MeterShack, Ruby Electronics, San Jose, USA) for each participant at each visit and the average luminance was 111lux (range 109-115lux).

2.2.2.2 Displays

Contrast sensitivity stimuli were presented on a 19" Sony Trinitron GDM-F520 CRT monitor (Sony, Tokyo, Japan) for which the display parameters are shown in Table 2.2. The screen was calibrated before each subject undertook contrast sensitivity measurement.

Parameter	Value
Test distance	2.0m
Angular size	10.81° × 8.11°
Frame rate	92Hz
Screen size	38.2 × 28.5cm
Screen resolution	1280 × 961
DPI	85
Screen luminance	50cd/m^2
Line scan rate	93.18
Clock rate	164.00

Table 2.2: Display parameters of Sony Trinitron monitor.

Adaptor stimuli were displayed on a 13.3" MacBook Pro (Apple Inc., Cupertino CA, USA), for which the display parameters are shown in Table 2.3. A matt grey cardboard surround was added to the screen to remove ambient distraction.

Parameter	Value
Test distance	0.50m
Angular size	29.7° × 19.7°
Aspect ratio	16:10
Screen size	28.5 × 18.0cm
DPI	113
Screen resolution	1280 × 800

Table 2.3: Display parameters of MacBook Pro.

2.2.2.3 Contrast sensitivity

Contrast sensitivity was measured using the Metropsis psychophysical vision-testing suite (Cambridge Research Systems, Rochester, UK). This PC-based software facilitated measurement of the contrast sensitivity function. A "protocol wizard," (including examples) enables the experimenter to input test parameters sequentially. The PC with Metropsis installed was connected to a ViSaGe visual stimulus generator (Cambridge Research Systems, Rochester, UK) that uses a 14-bit colour (greyscale resolution) and luminance control. A calibration device was supplied and the software had integrated support for gamma correction and colour calibration, ensuring stimulus luminance and chromaticity characteristics were precisely defined in an enhanced dynamic range. A CB6 push button response box (Figure 2.1) recorded participant's responses via wireless infrared link to the ViSaGe.

Figure 2.1: CB6 push-button response box

2.2.3 Test stimuli

The contrast sensitivity test stimuli were Gabor patches. They are the stimuli of choice in vision research (Smyth, Willmore, Baker, Thompson & Tolhurst, 2003) as they effectively model the receptive field characteristics of simple cells in the visual cortex (Marčelja, 1980). The Gabor patch consists of a sinusoidal grating whose amplitude is modulated by a two dimensional Gaussian window. The grating therefore blends smoothly with the background luminance, thus eliminating sharp edges from the stimulus that might otherwise alter the

perceived spatial frequency and the resultant contrast threshold. Furthermore, the Gabor form minimises localisation uncertainties (Stork & Wilson, 1990).

The Gabor produced by Metropsis was radially symmetrical with equal standard deviations θ_x and θ_y. The full width of a Gabor at half of maximum amplitude was 2.35 standard deviations. Although the extent of a Gaussian is infinite, its amplitude asymptotes toward zero within a few standard deviations and the Metropsis software ensures the Gabor patch is large enough to represent the complete envelope to a resolution of better than 1 least significant bit. The orientation of the Gabor patches were set at the Metropsis default of 90°, and therefore orientated vertically (Figure 2.2). The stimuli subtended a visual angle of 0.5° at a test distance of 2.0m. A raised cosine envelope was used to minimise the appearance of sharp temporal transients in the stimulus that might otherwise facilitate detection even when the spatial pattern is difficult to see.
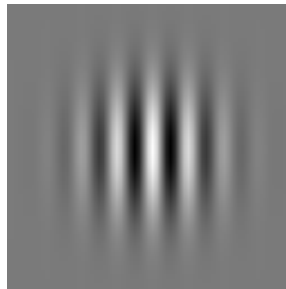
Figure 2.2: Gabor test stimulus for experiment 1.

Contrast sensitivity was measured for 5 spatial frequencies: 1, 2, 4.8, 9.6 and 19.1cdeg^{-1}. The text row frequency was calculated to be 1.6cdeg^{-1} (see adaptor stimuli, below) however Metropsis was unable to generate a test grating of 1.6cdeg^{-1} at the 2.0m viewing distance. Therefore contrast sensitivity was measured for both 1 and 2cdeg^{-1} to detect any adaptation effect from the text row frequency. 9.6cdeg^{-1} was selected to measure adaptation effects from the text stroke frequency. 4.8cdeg^{-1} was selected as it approximates the spatial frequency to which the human eye is most sensitive (Campbell & Robson, 1968), and 19.1cdeg^{-1} was chosen as a higher spatial frequency to complete the contrast sensitivity function.

2.2.4 Adaptor stimuli
2.2.4.1 Uniform white noise adaptor
A uniform white noise adaptor was generated in MATLAB (The Mathworks, Inc. Natick MA, USA), the spatial resolution of which was 1280 × 800 and Michelson contrast of 1. Figure 2.3 shows a sample of the stimulus whilst Figure 2.4 shows a Fast Fourier Transform (FFT) of the stimulus. Panel A) shows the normalised luminance profile for the horizontal screen resolution and Panel B) shows the amplitude spectrum for spatial frequencies distribution within the stimulus.
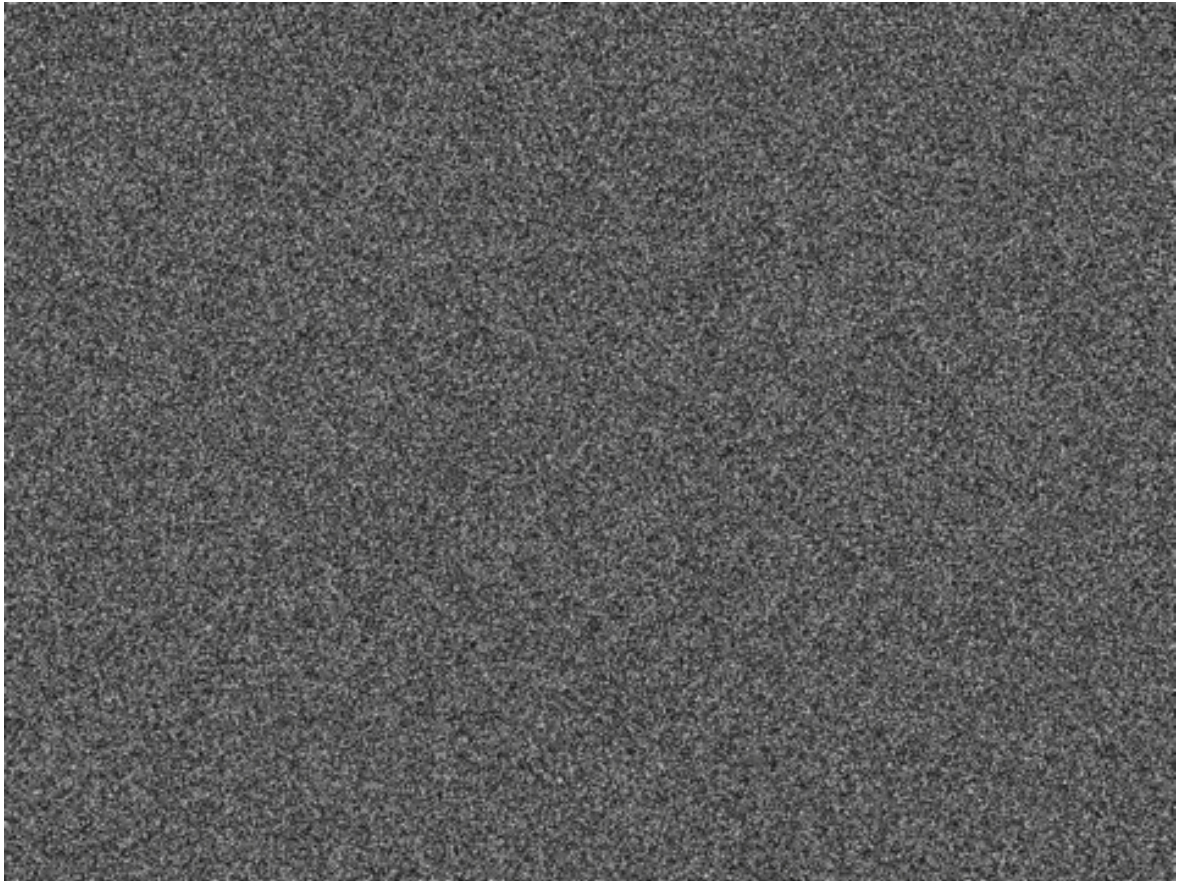
Figure 2.3: Sample of the white noise adaptor.
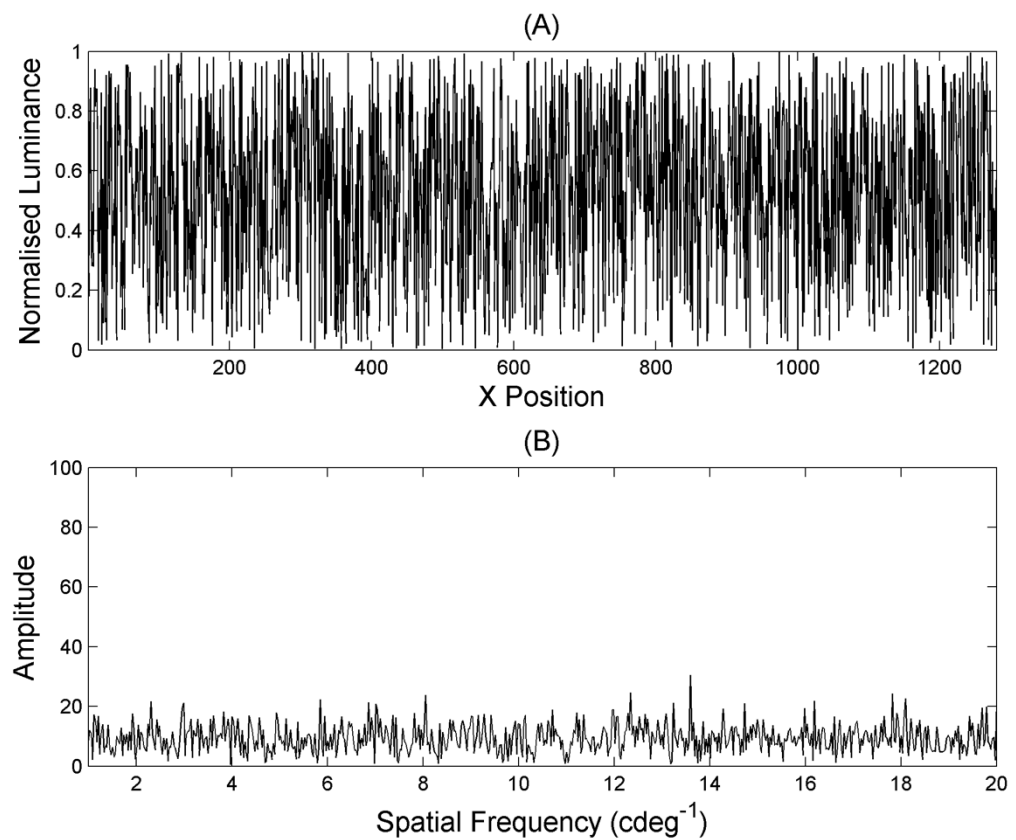
Figure 2.4: Fourier transform of uniform white noise stimulus. A) normalised luminance profile for the horizontal screen resolution. B) Amplitude of spatial frequencies illustrating no specific bias to any particular spatial frequency.

2.2.4.2 Text adaptor

Participants read high contrast English text taken from the novel "The Da Vinci Code," (Transworld Publishers, London, UK). The font used was Times New Roman, point size 12, single spaced, and formatted into PowerPoint slides and presented as a slide show on the MacBook Pro 50cm from the subject. Paragraph indentations and chapter breaks were erased to create continuous prose. Sufficient text was formatted to ensure participants did not have to read any slide more than once to encourage interest in the task and optimise potential adaptation. Figure 2.5 shows a sample of the text adaptor, the spatial resolution of which was 1280 × 800.

Louvre Museum, Paris 10:46 P. M. Renowned curator Jacques Saunire staggered through the vaulted archway of the museum's Grand Gallery. He lunged for the nearest painting he could see, a Caravaggio. Grabbing the gilded frame, the seventy-six-year-old man heaved the masterpiece toward himself until it tore from the wall and Saunire collapsed backward in a heap beneath the canvas. As he had anticipated, a thundering iron gate fell nearby, barricading the entrance to the suite. The parquet floor shook. Far off, an alarm began to ring. The curator lay a moment, gasping for breath, taking stock. I am still alive. He crawled out from under the canvas and scanned the cavernous space for someplace to hide. A voice spoke, chillingly close. "Do not move." On his hands and knees, the curator froze, turning his head slowly. Only fifteen feet away, outside the sealed gate, the mountainous silhouette of his attacker stared through the iron bars. He was broad and tall, with ghost-pale skin and thinning white hair. His irises were pink with dark red pupils. The albino drew a pistol from his coat and aimed the barrel through the bars, directly at the curator. "You should not have run." His accent was not easy to place. "Now tell me where it is." "I told you already," the curator stammered, kneeling defenseless on the floor of the gallery. "I have no idea what you are talking about!" "You are lying." The man stared at him, perfectly immobile except for the glint in his ghostly eyes. "You and your brethren possess something that is not yours. "The curator felt a surge of adrenaline. How could he possibly know this? "Tonight the rightful guardians will be restored. Tell me where it is hidden, and you will live." The man leveled his gun at the curator's head. "Is it a secret you will die for?" Saunire could not breathe. The man tilted his head, peering down the barrel of his gun. Saunire held up his hands in defense. "Wait," he said slowly. "I will tell you what you need to know." The curator spoke his next words carefully. The lie he told was one he had rehearsed many times… each time praying he would never have to use it. When the curator had finished speaking, his assailant smiled smugly. "Yes. This is exactly what the others told me." Saunire recoiled. The others? "I found them, too," the huge man taunted. "All three of them. They confirmed what you have just said." It cannot be! The curator's true identity, along with the identities of his three senchaux, was almost as sacred as the ancient secret they protected. Saunire now realized his senchaux, following strict procedure, had told the same lie before their own deaths. It was part of the protocol. The attacker aimed his gun again. "When you are gone, I will bethe only one who knows the truth. "The truth. In an instant, the curator grasped the true horror of the situation. If I die, the truth will be lost forever. Instinctively, he tried to scramble for cover. The gun roared, and the curator felt a searing heat as the bullet lodged in his stomach. He fell forward... Struggling against the pain. Slowly, Saunire rolled over and stared back through thebars at his attacker. The man was now taking dead aim at Saunire's head. Saunire closed his eyes, his thoughts a swirling tempest of fear and regret. The click of an empty chamber echoed through the corridor. The curator's eyes flew open. The man glanced down at his weapon, looking almost amused. He reached for a second clip, butthen seemed to reconsider, smirking calmly at Saunire's gut. "My work here is done." The curator looked down and saw the bullet hole in his white linen shirt. It was framed by a small circle of blood a few inches below his breastbone. My stomach. Almost cruelly, the bullet had missed his heart. As a veteran of la Guerre d'Algrie, the curator had witnessed this horribly drawn-out death before. For fifteen minutes, he would survive as his stomach acids seeped into his chest cavity, slowly poisoning him from within. "Pain is good, monsieur," the man said. Then he was gone. Alone now, Jacques Saunire turned his gaze again to the iron gate. He was trapped, and the doors could not be reopened for at least twenty minutes. By the time anyone got to him, he would be dead. Even so, the fear that now gripped him was a fear far greater than that of his own death. I must pass on the secret. Staggering to his feet, he pictured his three murdered brethren. He thought of the generations who had come before them... Of the mission with which they had all been entrusted. An unbroken chain of knowledge. Suddenly, now, despite all the precautions... Despite all the fail-safes... Jacques Saunire was the only remaining link, the sole guardian of one of the most powerful secrets ever kept. Shivering, he pulled himself to his feet. I must find some way.... He was trapped inside the Grand Gallery, and there existed only one person on earth to whom he could pass the torch. Saunire gazed up at the walls of his opulent most powerful secrets ever kept. Shivering, he pulled himself to his feet. I must find some way.... He was trapped inside the Grand Gallery, and there existed only one person on earth to whom he could pass the torch. Saunire gazed up at the walls of his opulent prison. A collection of the world's most famous paintings seemed to smile down on him like old friends. Wincing in

Figure 2.5: A sample of the high contrast text adaptor.

To calculate text row frequency, the text was likened to the black bars of a grating whilst the space between rows of text likened to the white bars of the grating (Figure 2.6).

Figure 2.6: Rows of text correspond to dark bars of Gabor grating whilst rows of inter-text space correspond to the light bars.

Figure 2.7 illustrates the trigonometric calculation used to calculate the text row spatial frequency created by the pattern formed by the lines and spacing of the text which was 1.6cdeg^{-1}.
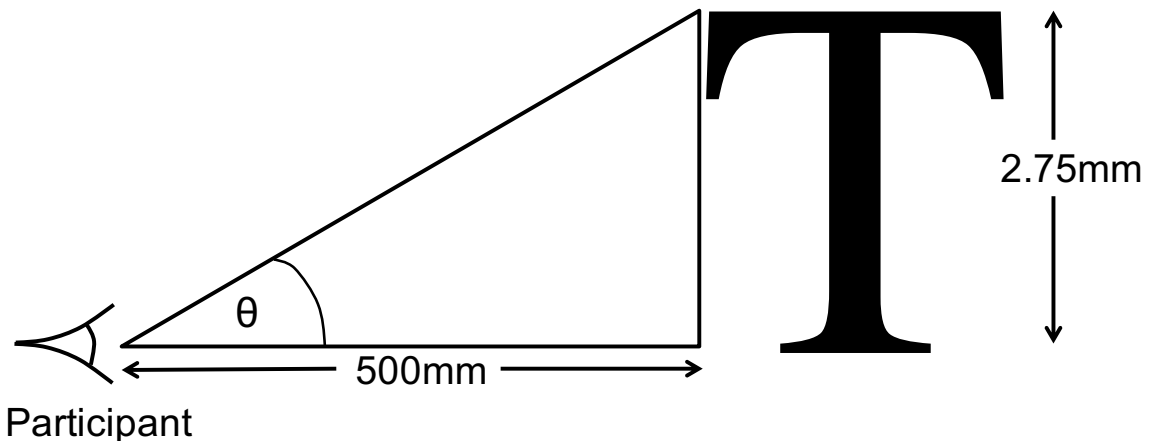
Figure 2.7: Trigonometric calculation of text row frequency based on letter height: letter height in mm h = 2.75mm and the distance to the screen from the observer d = 500mm, the angle of elevation from the observer, measured in degrees, was given by tan^{-1}(h ÷ d) = 0.30° This was multiplied by 60 minutes of arc = 18.18 minutes per degree of visual angle. 1 row of text + one row of inter-text space = 1 cycle, ∴ 1 cycle = 2 × 18.18 = 36.36. Dividing this into 60 minutes of arc = 1.6cdeg^{-1}.

Majaj et al., (2002) suggested that the stroke frequency created by letters was the '*sole determinant of the channel frequency*' that observers used in letter perception, given by the formula , $f_{channel}$ / 10cdeg^{-1} = (f_{stroke} / 10cdeg^{-1})$^{2/3}$. Thus, stroke frequency was calculated as described in their methods (Figure 2.8). A horizontal line was drawn through a row of text

at half the height of a lower case letter and the number of vertical strokes crossing this line were counted and repeated for first 30 rows of text. Average stroke frequency was calculated by dividing the average number of strokes across all rows by the horizontal screen size in degrees and was equal to 9.6cdeg^{-1}.

Figure 2.8: Comparison of stroke frequency as calculated by the stroke counting technique described by Majaj et al. (2002). The technique is repeated 3 times in this figure to illustrate different stroke frequencies for the same point size text produced in 3 different fonts: A) Times New Roman; B) Calibri; C) Verdana.

2.2.5 Procedure

2.2.5.1 Quest

Methods for estimating stimulus threshold can be broadly grouped into *methods of constant stimuli* and *adaptive procedures* (Macmillan, 2001). The aforementioned Metropsis protocol wizard offers three adaptive psychophysical procedures including Linear staircase, Logarithmic staircase and QUEST. Pelli and Bex (2013) suggested adaptive procedures be used, specifically QUEST, as the contrast sensitivity test of choice if the test is not printed. QUEST has been shown to be more accurate and efficient (Watson & Fitzhugh, 1990) for an equivalent number of trials, and thus QUEST procedures were used for all experimental work in this thesis.

The QUEST algorithm was introduced by Watson and Pelli (1983). It employs a Bayesian framework for combining prior knowledge with the results of previously completed trials to model participants' contrast sensitivity as a probability density function (PDF: the relative probability of different thresholds in the population). As participants respond, the PDF narrows as QUEST improves its understanding of their contrast threshold in an attempt to minimise the variance of the final threshold estimate. Having input an initial threshold close to the anticipated final threshold, the observer's response to previous trials is used to determine the threshold of subsequent trials. This process is repeated either for a fixed number of stimulus presentations or until the probability distribution has tightened to achieve a desired confidence level.

QUEST was set to terminate after 50 trials. For the QUEST, threshold is calculated as the peak value in the final PDF. Confidence is defined as the proportion of area under this PDF curve that lies within a 2% contrast interval to the right of threshold. Figure 2.9 details how Metropsis calculates the final contrast threshold and standard deviation.
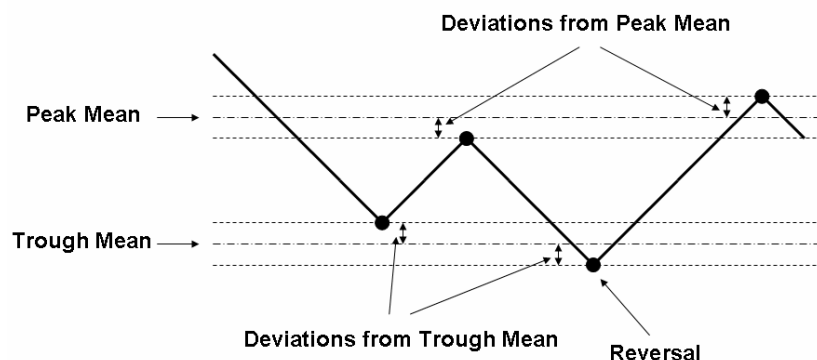
Figure 2.9: The final contrast threshold is determined as the midpoint between the peak and trough means. The deviation from the peak and trough reversals (black points) from their mean (dashed black lines) is squared and averaged to obtain peak and trough variance. Threshold standard deviation is calculated by taking the square root of the variances, and then averaging.

The stimulus presentation duration was set at 800ms, the default value in the Metropsis protocol wizard. Every 30th trial was presented 10% above the current contrast for that spatial frequency as a motivational trial to keep the participant interested. The response of this trial was not used to compute the result.

The mean screen luminance (l_{mean}) was used as the background luminance on which the stimulus was presented and around which the stimulus contrast was modulated. The default value is half of the maximum luminance of the stimulus monitor, and so was set to 50cd/m^2.

The positive and negative response confirmations are, by default, both set to one, meaning that the stimulus contrast was modified with each participant response. If the number of confirmations is set too low, for example, it would require two correct or incorrect responses at a given spatial frequency before the stimulus contrast is modified. This may actually reduce the length of the test for some subjects, as it helps to filter out errors in which the participant accidentally presses the wrong button.

The contrast sensitivity test protocol was explained to participants, who were then given the opportunity to practice until confident with the procedure. In the QUEST procedure, initial contrast values define the default contrast at which stimuli are first displayed. To determine the initial threshold, each participant undertook one trial of a linear staircase procedure with an undefined number of trials for each spatial frequency. A contrast value slightly higher than the resultant threshold of the linear staircase was entered as the initial contrast for the adaptive procedure to ensure accurate convergence within the fixed number of trials. The initial contrast was set independently for each spatial frequency in the protocol wizard. If the initial contrast value is set too high, there is a risk that the QUEST procedure would not give an accurate final value for the contrast threshold.

2.2.5.2 Experimental paradigm

Figure 2.10 shows the experimental setup for Experiment 1. Participants were seated at the edge of an optical bench and positioned at a chin rest and brow bar and corrected with full-aperture trial case lenses. The sphero-cylinder distance refractive correction was placed in lens mounts in front of each eye. Contrast stimuli were presented on the Sony Trinitron monitor at 2.0m from the subject, for whom an additional +0.50DS was added to the refractive correction. When viewing the adaptor stimulus on the MacBook Pro laptop at 0.5m, an additional +1.50D full aperture trial lens was placed before each eye. The laptop was raised and lowered as required to enable adaptor presentation or contrast sensitivity measurement, and the refractive correction was altered to fully relax accommodation for the respective viewing distances.
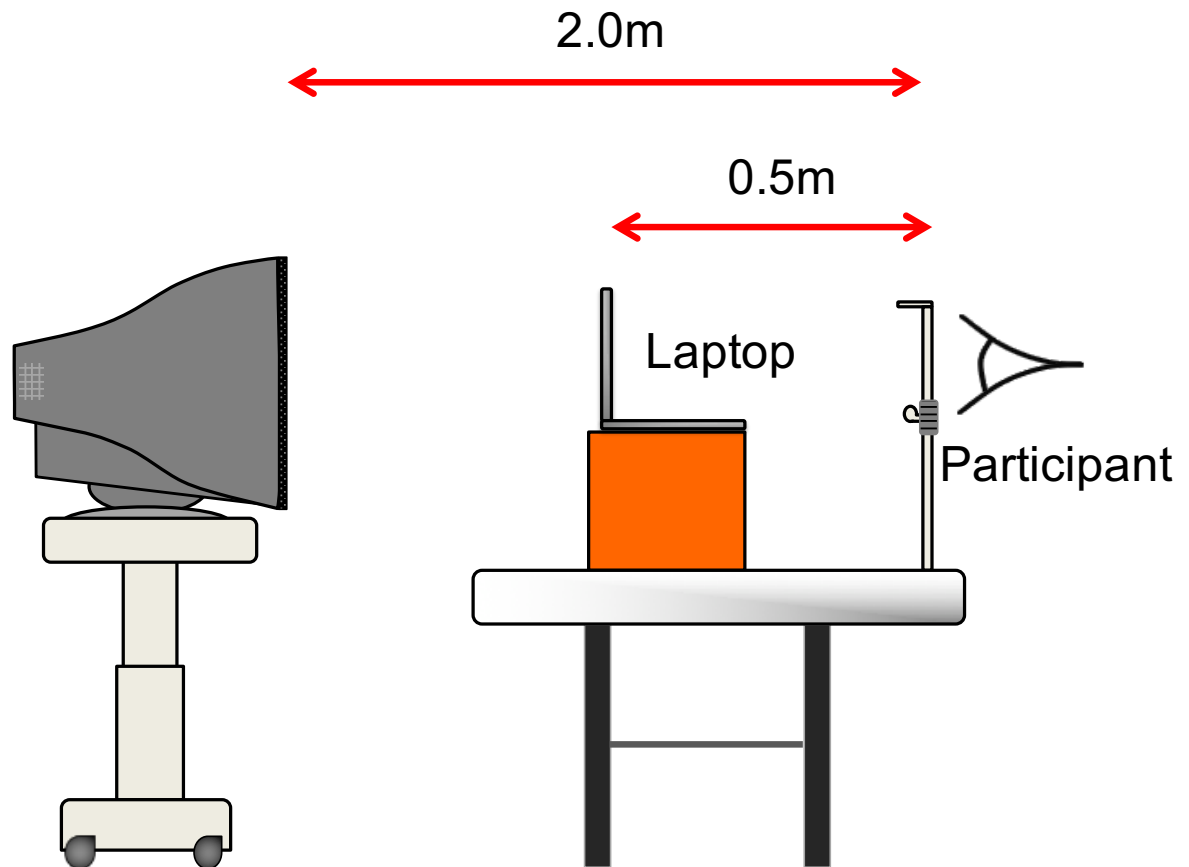
Figure 2.10: Schematic of experimental setup for Experiment 1.

Psychophysical procedures of forced choice tests rely upon certain assumptions about participants' behaviour when they are unsure about the stimulus presentation. Specifically, it is assumed that they respond to an uncertain stimulus presentation with their best guess and so they were instructed to do so. The experimental paradigm was a Two Alternative Forced Choice (2AFC): button A (red, top or bottom) of the CB6 response box (Figure 2.1) was pressed if a stimulus was seen to the left of the fixation target, and button B (yellow, top or bottom) was pressed if the stimulus was detected to the right of their central fixation.

The values obtained from the initial staircase procedures were entered into the QUEST protocol. Pre-adaptation contrast sensitivity was recorded for the five spatial frequencies: one staircase for each stimulus frequency was run for 50 trials for each spatial frequency. The five tested frequencies were interwoven randomly, and the QUEST protocol took an average of eight minutes to complete. An audible beep denoted the commencement of the contrast sensitivity measurement and participants' responses.

The MacBook was then placed before participants and a grey neutral surround (see section 2.2.2.2) was added to the screen to remove ambient distraction. Additional full-aperture trial case lenses were added to account for the closer viewing distance, and the uniform white noise adaptor was presented for 30mins. Participants were encouraged to constantly alter their fixation upon the screen surface whilst viewing the noise adaptor to minimise the

influence of figural aftereffects. After 30mins, the additional lenses were removed and participants completed post-white noise adaptation contrast sensitivity measurement, as before.

Following this, the laptop, surround, and additional plus powered lenses were once again placed before participants, who then read the text adaptor on the screen continuously for 30mins. Participants left clicked a mouse to progress to the next slide. They were not tested for reading speed or comprehension of the text. Post-text adaptation contrast sensitivity was measured immediately after reading. The supplementary lenses were removed and the participants fixated again at the 2m viewing distance. All contrast sensitivity measurements were then extracted from the Metropsis software and recorded in an Excel spreadsheet prior to analysis.

2.2.6 Statistical design

The data obtained were percentage contrast thresholds. For statistical analysis, contrast thresholds were expressed as the common logarithm of the reciprocal of the threshold contrast, i.e. log contrast sensitivity ($\log_{10}CS$). Thus, a threshold of 0.01 (1%) represented a contrast sensitivity of 100 or a $\log_{10}CS$ of 2.0, a threshold of 0.0114 (1.14%) represented a contrast sensitivity of 87.7 or a $\log_{10}CS$ of 1.94. Pre-adaptation $\log_{10}CS$ and post adaptation $\log_{10}CS$, and changes in $\log_{10}CS$ pre-post adaptation were entered into SPSS v20 statistical software for analysis (version 20, IBM Corp., Armonk, NY, USA).

A 3×5×2 mixed ANOVA was run with $\log_{10}CS$ as the dependent variable. The first within subjects factor was adaptation state, with three levels (pre-adaptation, post-noise and post-text adaptation). The second within subjects factor was spatial frequency with five levels (1, 2, 4.8, 9.6 and 19.1$cdeg^{-1}$). The between subjects factor was participant group, with two levels (myopic and emmetropic).

A 2×5×2 mixed ANOVA was run with $\log_{10}CS$ adaptation as the dependent variable. The first within subjects factor was adaptation, with two levels (pre-post-noise adaptation, and post-noise – post-text adaptation). The second within subjects factor was spatial frequency with five levels (1, 2, 4.8, 9.6 and 19.1 cdeg-1). The between subjects factor was participant group, with two levels (myopic and emmetropic).

2.3 Results

2.3.1 Pre-adaptation contrast sensitivity

Contrast sensitivity was measured at 1, 2, 4.8, 9.6 and 19.1$cdeg^{-1}$. The peak pre-adaptation contrast sensitivity was 2.00 ± 0.17 log units at 2$cdeg^{-1}$, and the lowest was 0.72 ± 0.29 log units at 19.1$cdeg^{-1}$ across all participants. There was a significant difference in pre-

adaptation $\log_{10}$CS between emmetropic and myopic participants at 19.1cdeg^{-1} (Bonferroni-corrected independent samples *t*-test $t_{(18)}$ = -3.38; $p < 0.01$), but not at the other spatial frequencies (1cdeg^{-1} $t_{(18)}$ = 0.70; p = 0.50; 2cdeg^{-1} $t_{(18)}$ = 1.54; p = 0.14; 4.8cdeg^{-1} $t_{(18)}$ = 0.08; p = 0.93; 9.6cdeg^{-1} $t_{(18)}$ = -1.95; p = 0.07).

2.3.2 Post-adaptation contrast sensitivity

Figure 2.11 shows the mean $\log_{10}$CS pre-adaptation, post-noise adaptation and post-text adaptation for each of the five tested spatial frequencies for (a) all participants, (b) emmetropes, and (c) and myopes. The peak post-adaptation contrast sensitivity was at 2cdeg^{-1} (2.01 ± 0.20 log units after noise adaptation and 2.10 ± 0.30 log units after text adaptation) and the lowest was at 19.1cdeg^{-1} (0.75 ± 0.28 log units after noise adaptation and 0.71 ± 0.30 log units after text adaptation across all participants.

A mixed ANOVA showed no significant difference in $\log_{10}$CS values pre-adaptation, post-noise and post-text adaptation [Wilks' Lambda = 0.95; $F_{(2,17)}$ = 0.41, p = 0.67, η_p^2 = 0.29]. There was a significant effect of spatial frequency [Wilks' Lambda = 0.03; $F_{(4,15)}$ = 135.78, $p < 0.01$, η_p^2 = 0.97] but no significant effect of participant group $F_{(1,18)}$ = 1.69, p = 0.21, η_p^2 = 0.09]. There was no significant interaction between $\log_{10}$CS and spatial frequency [Wilks' Lambda = 0.57; $F_{(8,11)}$ = 1.06, p = 0.46, η_p^2 = 0.43], or between $\log_{10}$CS and participant group [Wilks' Lambda = 0.96; $F_{(2,17)}$ = 0.32, p = 0.73, η_p^2 = 0.04]. However, a significant interaction between spatial frequency and participant group was found [Wilks' Lambda = 0.54; $F_{(4,15)}$ = 3.12, p = 0.05, η_p^2 = 0.46]. The interaction means that the effect of spatial frequency on $\log_{10}$CS is different for myopes and emmetropes. There was no significant interaction between $\log_{10}$CS, spatial frequency and participant group [Wilks' Lambda = 0.60; $F_{(8,11)}$ = 0.91, p = 0.54, η_p^2 = 0.40].
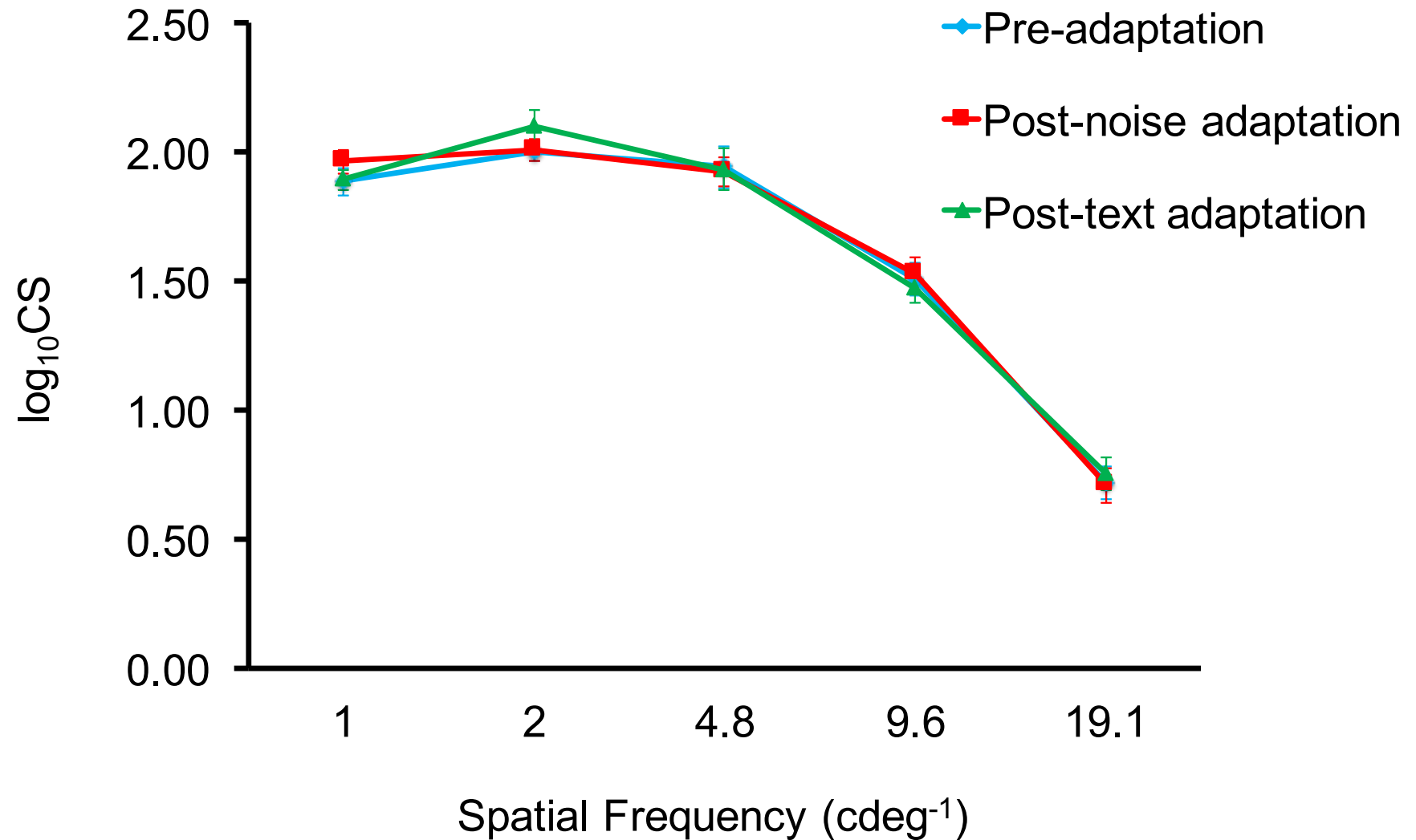
Figure 2.11a: Mean pre-adaptation, post-noise adaptation and post-text adaptation $\log_{10}CS$ for all participants. Error bars show ± 1 SEM.
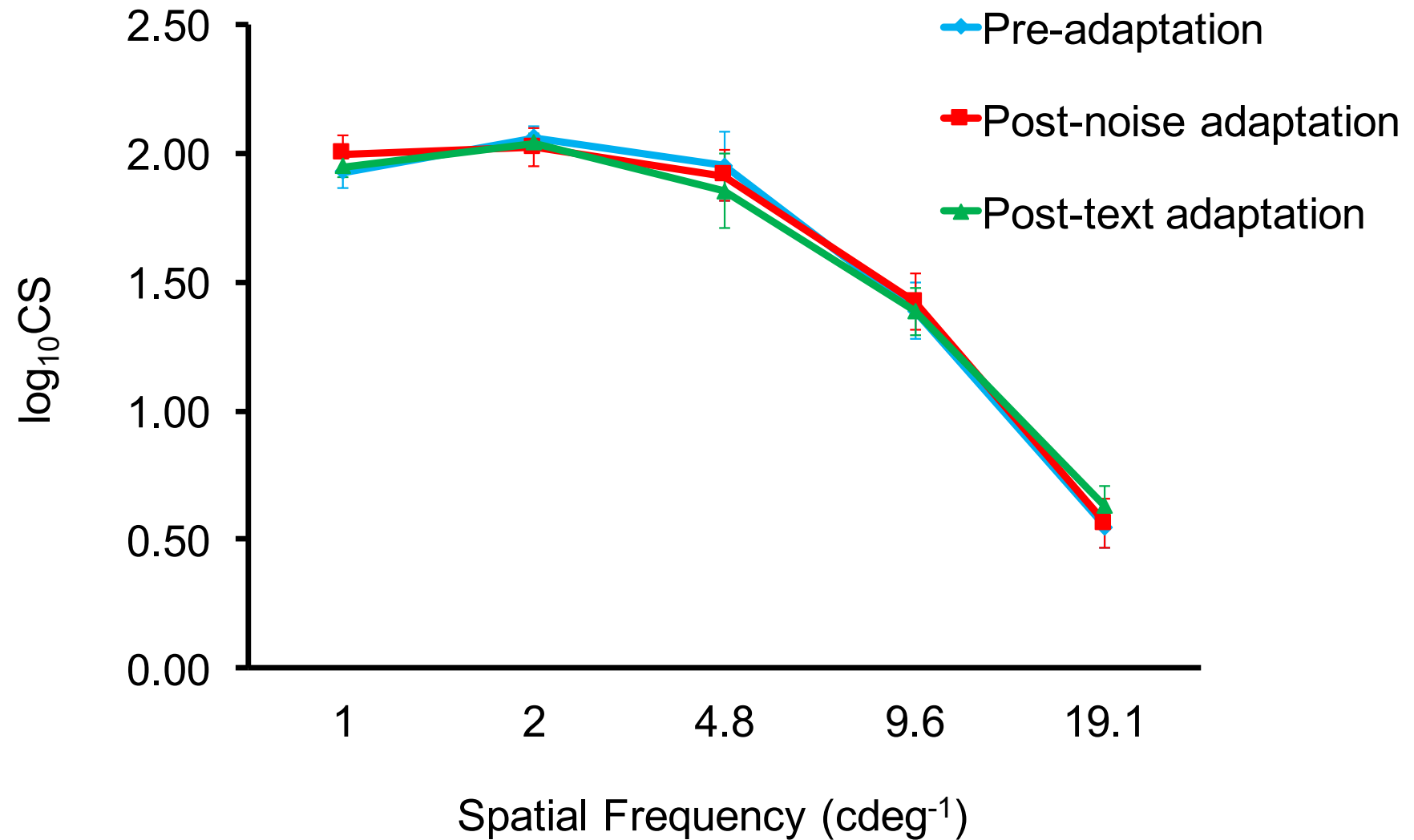
Figure 2.11b: Mean pre-adaptation, post-noise adaptation and post-text adaptation $\log_{10}CS$ for emmetropic participants. Error bars show ± 1 SEM.
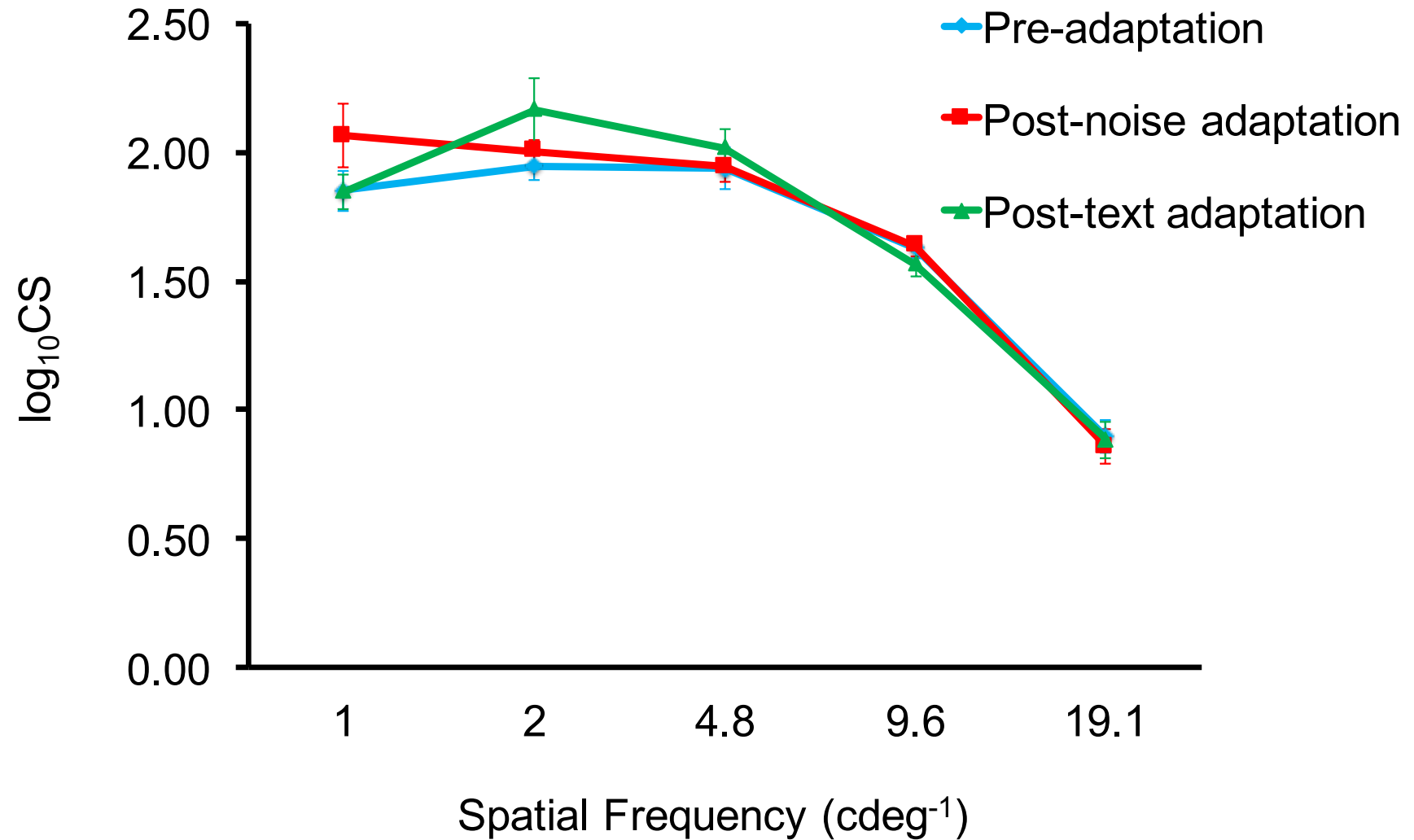
Figure 2.11c: Mean pre-adaptation, post-noise adaptation and post-text adaptation $\log_{10}CS$ for myopic participants. Error bars show $\pm$ 1 SEM.

2.3.3 Contrast adaptation

Contrast adaptation was defined as the magnitude of change in $\log_{10}$CS pre-post noise adaptation (range: 0 to 0.08 log units for all participants) and post-noise – text adaptation (range: 0 to 0.16 log units for all participants).

For all spatial frequencies, the mean contrast adaptation pre-post noise adaptation was 0.02 ± 0.03 log units (mean ± SEM) and the greatest magnitude of contrast adaptation was at 1cdeg^{-1} (0.08 ± 0.05 log units).

The mean contrast adaptation post-noise – text adaptation was 0.01 ± 0.06 log units (mean ± SEM) and the greatest magnitude of contrast adaptation was at 2cdeg^{-1} (0.09 ± 0.08 log units).

Table 2.4 shows mean contrast adaptation ± SEM pre-post noise adaptation and post-noise – text contrast adaptation in all, emmetropic, and myopic participants.

SF (cdeg^{-1})		Pre-post noise adaptation					Post-noise – text adaptation				
		1	2	4.8	9.6	19.1	1	2	4.8	9.6	19.1
Mean	All	0.08	0.01	-0.02	0.02	-0.01	-0.07	0.09	0.01	-0.05	0.05
$\log_{10}$CS		±0.05	±0.05	±0.06	±0.04	±0.04	±0.06	±0.07	±0.05	±0.05	±0.03
adaptation	Emm	0.07	-0.04	-0.04	0.04	0.02	-0.05	0.02	-0.06	-0.04	0.06
± SD		±0.07	±0.08	±0.09	±0.06	±0.03	±0.07	±0.07	±0.07	±0.08	±0.03
	My	0.08	0.06	0.01	0.01	-0.04	-0.09	0.16	0.07	-0.07	0.03
		±0.09	±0.04	±0.08	±0.04	±0.04	±0.09	±0.13	±0.06	±0.06	±0.06

Table 2.4: Mean contrast adaptation ± SEM in all participants, emmetropes (Emm) and myopes (My). Contrast adaptation was not statistically significant post-noise adaptation or post text adaptation.

A mixed ANOVA was run to compare $\log_{10}$CS adaptation after noise vs. after text adaptation. There were no significant main effects of $\log_{10}$CS adaptation [Wilks' Lambda = 0.99; $F_{(1,18)}$ = 0.81, p = 0.78, η_p^2 = 0.04], spatial frequency [Wilks' Lambda = 0.81; $F_{(4,15)}$ = 0.90, p = 0.49, η_p^2 = 0.19], or participant group [$F_{(1,18)}$ = 0.66, p = 0.45, η_p^2 = 0.04]. There were no significant interactions between $\log_{10}$CS adaptation and spatial frequency [Wilks' Lambda = 0.72; $F_{(4,15)}$ = 1.47, p = 0.26, η_p^2 = 0.28], $\log_{10}$CS adaptation and participant group [Wilks' Lambda = 0.99; $F_{(1,18)}$ = 0.07, p = 0.80, η_p^2 = 0.04], or spatial frequency and participant group [Wilks' Lambda = 0.65; $F_{(4,15)}$ = 1.99, p = 0.15, η_p^2 = 0.35]. Furthermore, there was no significant 3-way interaction between $\log_{10}$CS adaptation, spatial frequency and participant group [Wilks' Lambda = 0.98; $F_{(4,15)}$ = 0.09, p = 0.15, η_p^2 = 0.02].

2.3.4 Correlation between $\log_{10}$CS and change in $\log_{10}$CS

The relationship between pre-adaptation $\log_{10}$CS and the magnitude of change in $\log_{10}$CS pre-post noise adaptation was examined. For all participants, statistically significant

negative correlations were observed for spatial frequencies 1cdeg^{-1} ($r_{(19)}$ = -0.66; $p < 0.01$), 2cdeg^{-1} ($r_{(19)}$ = -0.46; $p = 0.04$) and 4.8cdeg^{-1} ($r_{(19)}$ = - 0.69; $p < 0.01$) as shown in Figure 2.12a. The effect size for these analyses exceed Cohen's (1988, 1992) convention for a medium effect size at 2cdeg^{-1} and a large effect size at 1 and 4.8cdeg^{-1}. When grouped by refractive error, emmetropic participants showed a statistically significant negative correlation at 4.8cdeg^{-1} ($r_{(9)}$ = -0.69; $p = 0.03$) as shown in Figure 2.12b. Myopic participants showed statistically significant negative correlations at 1.0 cdeg^{-1} ($r_{(9)}$ = -0.81; $p < 0.01$) and 4.8 cdeg^{-1} ($r_{(9)}$ = -0.71; $p = 0.02$) as shown in Figure 2.12c (all large effect sizes by Cohen's convention).

Significant negative correlations were also observed between post-noise log$_{10}$CS and the change in log$_{10}$CS post-noise – text adaptation. For all participants, the correlation was significant (2 tailed) at 1.0cdeg^{-1} ($r_{(19)}$ = -0.73; $p < 0.01$), 2.0cdeg^{-1} ($r_{(19)}$ = -0.47; $p = 0.03$) and 9.6cdeg^{-1} ($r_{(19)}$ = -0.51; $p = 0.02$) as shown in Figure 2.13a. The effect size for these analyses exceed Cohen's (1988, 1992) convention for a medium effect size at 2cdeg^{-1} and a large effect size at 1 and 9.6cdeg^{-1}. When grouped by refractive error, emmetropic participants showed a statistically significant negative correlation at 1cdeg^{-1} ($r_{(9)}$ = -0.86 $p < 0.01$) and 2cdeg^{-1} ($r_{(9)}$ = -0.87; $p < 0.01$), all of which are large effect sizes by Cohen's convention as shown in Figure 2.13b. Myopic participants did not show any significant correlation between post-noise log$_{10}$CS and the change in log$_{10}$CS post-noise – text adaptation for any spatial frequency (Figure 2.13c).
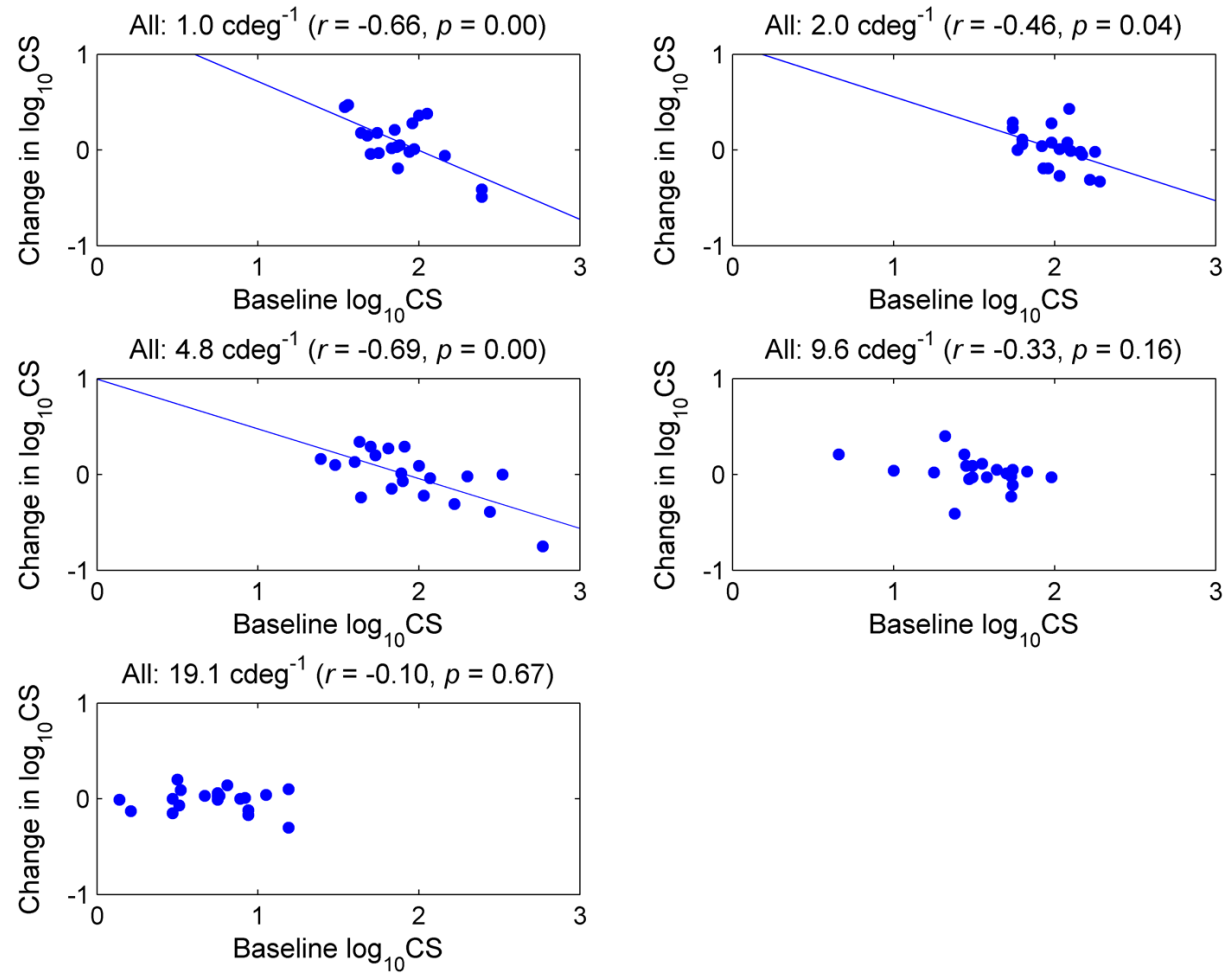
Figure 2.12a: Correlation between pre-adaptation $\log_{10}$CS and the change in $\log_{10}$CS pre-post noise adaptation for all participants. Best fit lines are shown were the correlation was significant.
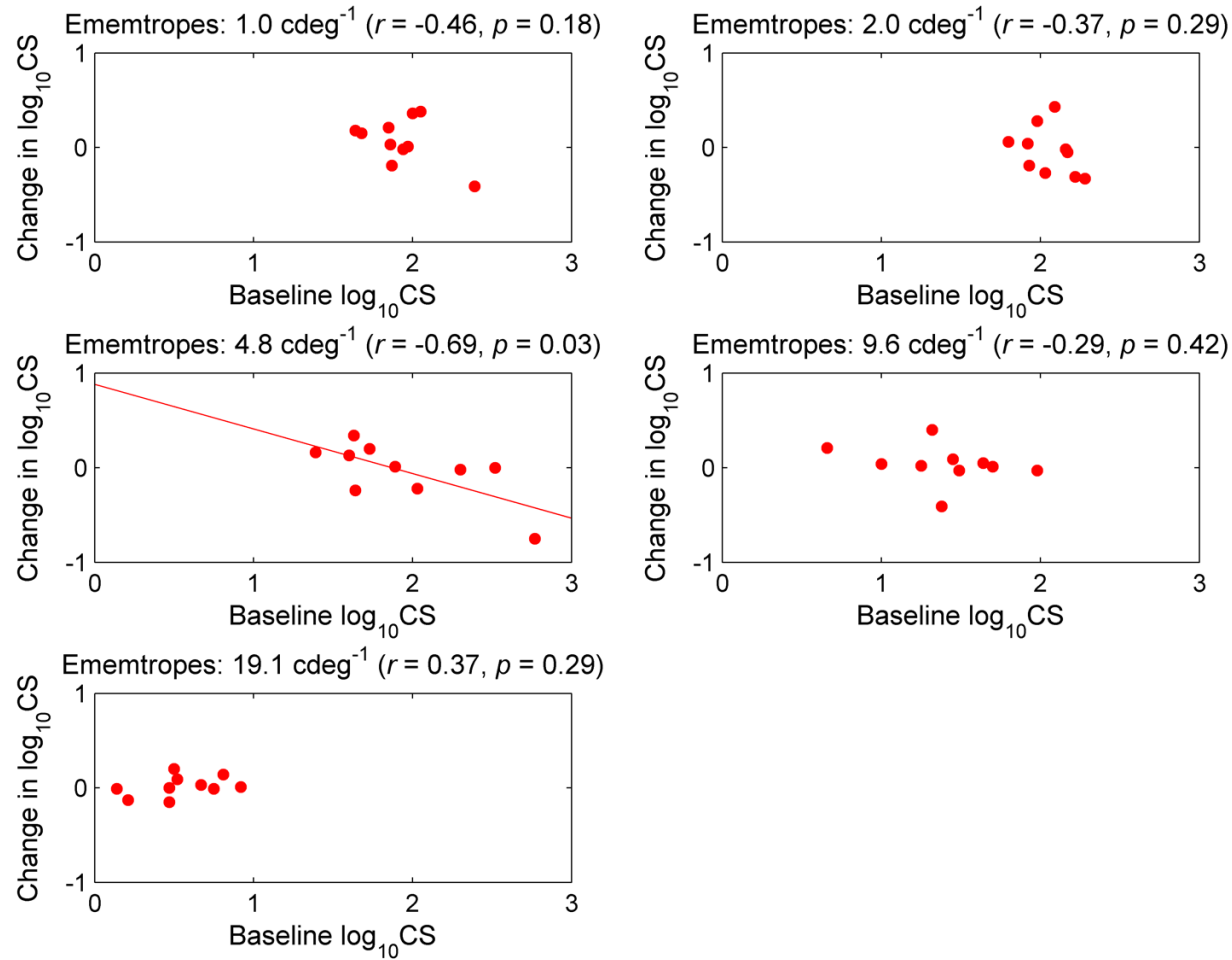
Figure 2.12b: Correlation between pre-adaptation $\log_{10}CS$ and the change in $\log_{10}CS$ pre-post noise adaptation for emmetropic participants. Best fit lines are shown were the correlation was significant.
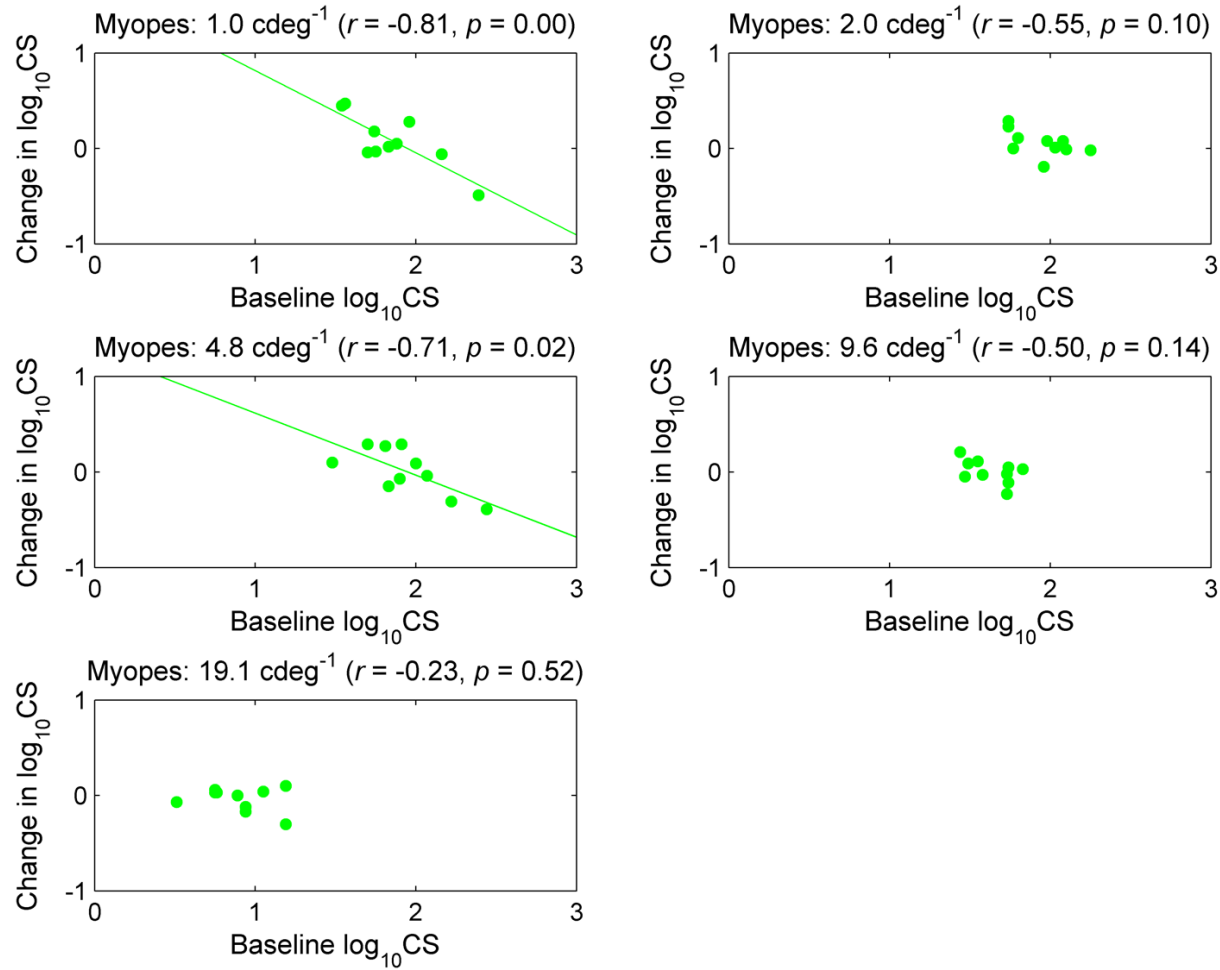
Figure 2.12c: Correlation between pre-adaptation $log_{10}CS$ and the change in $log_{10}CS$ pre-post noise adaptation for myopic participants. Best fit lines are shown were the correlation was significant.
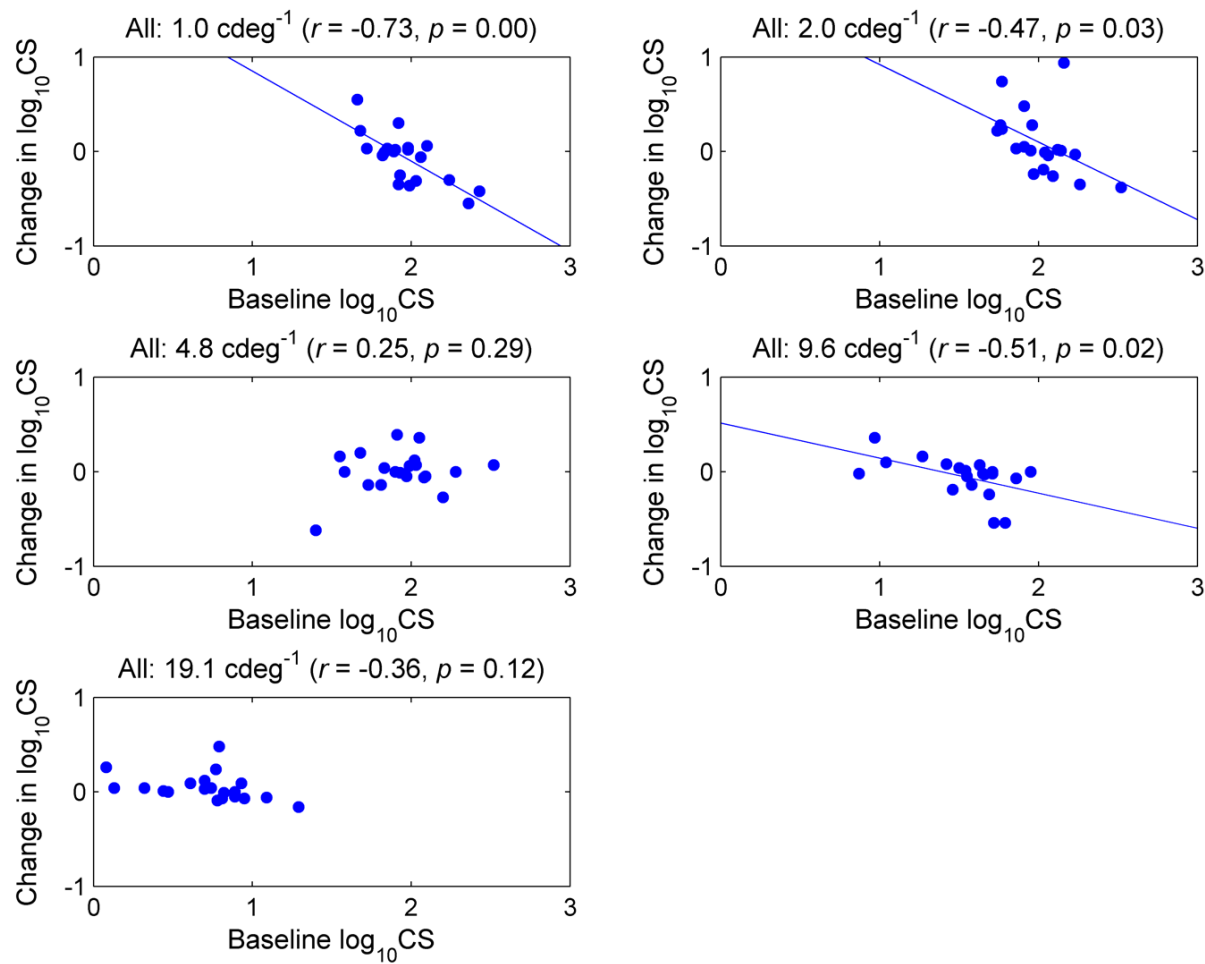
Figure 2.13a: Correlation between $\log_{10}CS$ post-noise adaptation and the change in $\log_{10}CS$ post-noise – text adaptation for all participants. Best fit lines are shown were the correlation was significant.
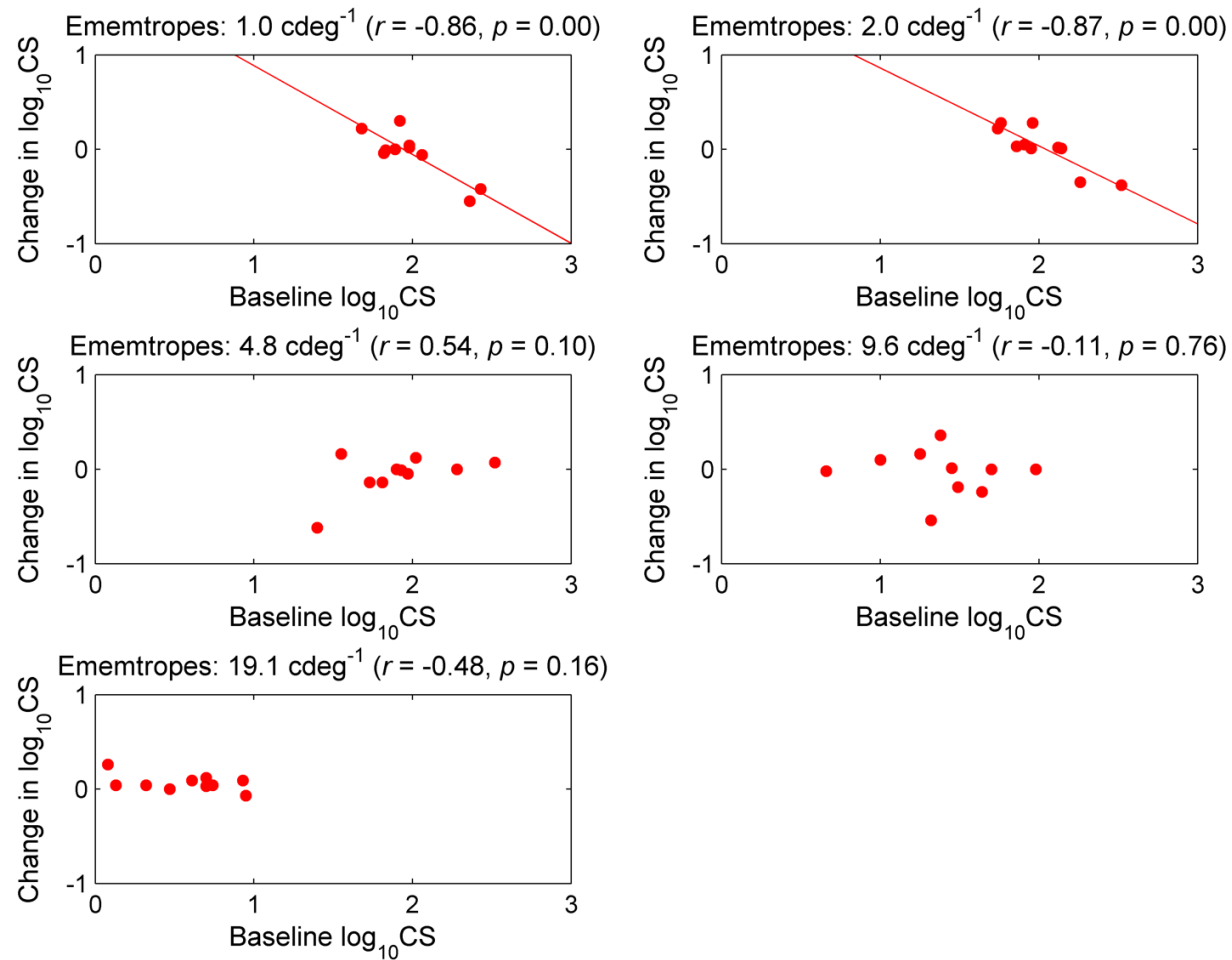
Figure 2.13b: Correlation between $\log_{10}CS$ post-noise adaptation and the change in $\log_{10}CS$ post-noise – text adaptation for emmetropic participants. Best fit lines are shown were the correlation was significant.
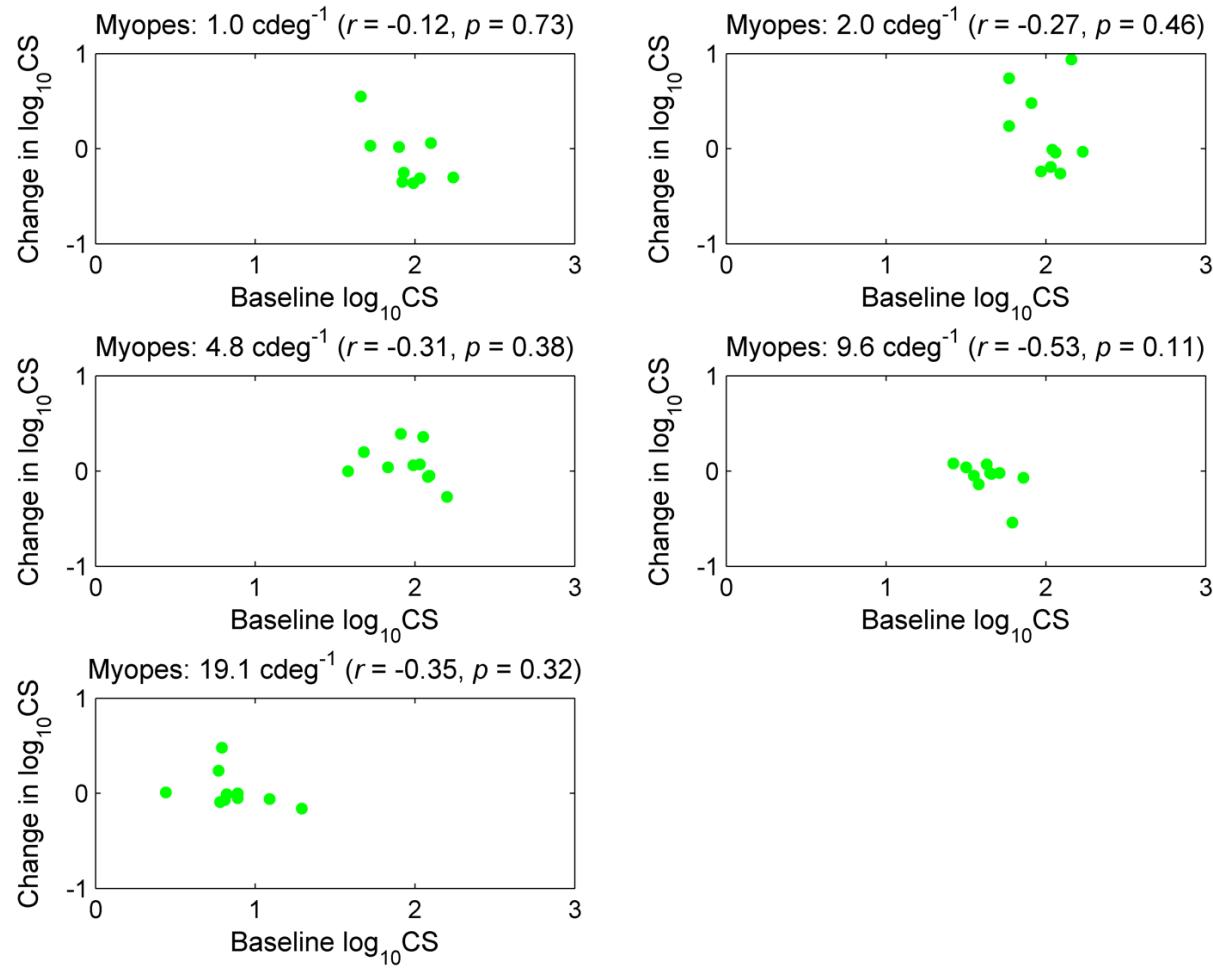
Figure 2.13c: Correlation between $\log_{10}$CS post-noise adaptation and the change in $\log_{10}$CS post-noise – text adaptation for emmetropic participants. Best fit lines are shown were the correlation was significant.

2.4 Discussion

2.4.1 Pre-adaptation contrast sensitivity

Figure 2.14 shows that the pre-adaptation contrast sensitivity was comparable to that reported in other studies.
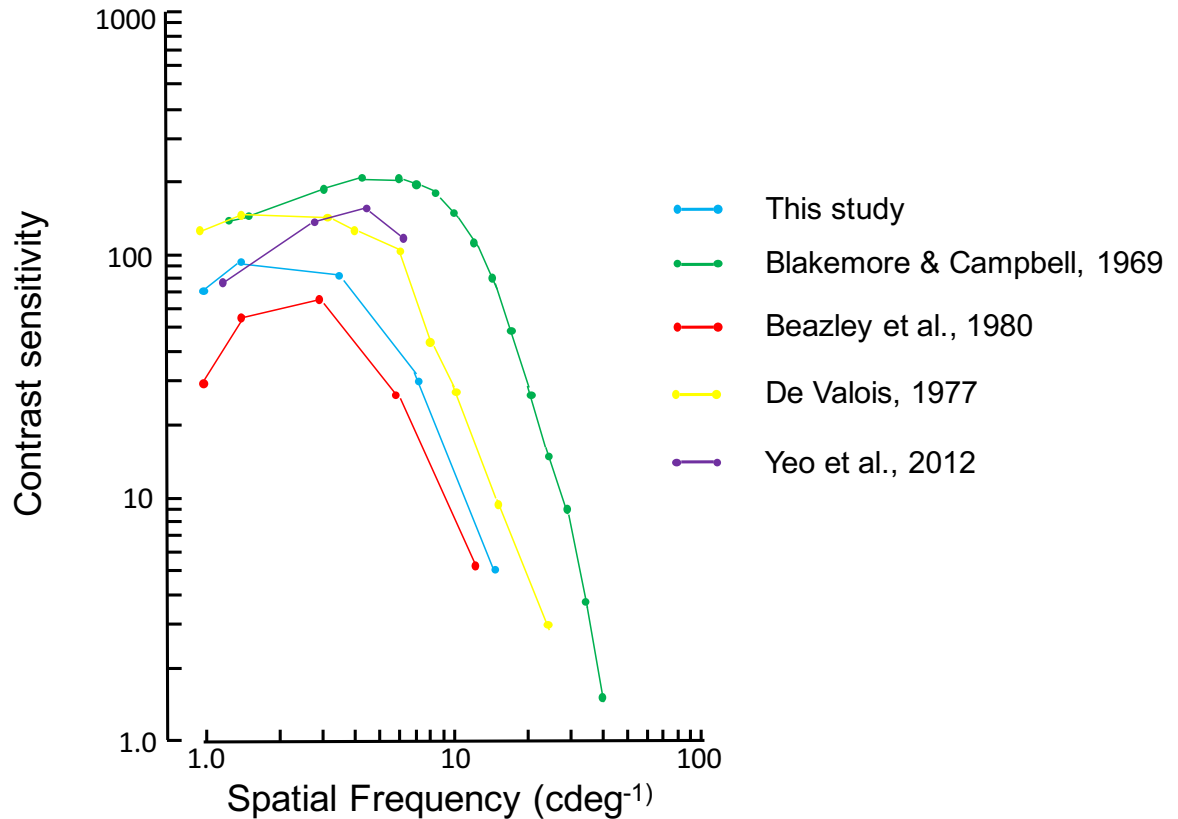
Figure 2.14: Pre-adaptation contrast sensitivity for this study compared to that reported for adult observers in other studies.

Various methodological differences may account for the variation in contrast sensitivity as shown above including the type of stimuli, mean luminance, psychophysical procedures, monocular vs. binocular measurements and utilisation of artificial pupils.

In the current study, mean $\log_{10}$CS was significantly different between emmetropes and myopes pre-adaptation at 19.1cdeg^{-1} but not for the other four spatial frequencies.

2.4.2 Post-adaptation contrast sensitivity

In this experiment, no significant contrast adaptation effect was measured after uniform white noise adaptation or adaptation to text on a screen. This is inconsistent with earlier studies that measured contrast adaptation after reading text on a screen (Lunn & Banks, 1986; Greenhouse et al., 1992; Magnussen et al., 1992) and printed text on a page (Yeo et al*.,* 2012). In addition, there were no measureable differences in contrast sensitivity between refractive error groups. Given the lack of contrast adaptation, it is therefore unsurprising that mean $\log_{10}$CS was significantly different between emmetropes and myopes post-white noise and post text adaptation only at 19.1cdeg^{-1}.

2.4.3 Addressing lack of contrast adaptation

This discussion will address the potential reasons as to why no change in contrast sensitivity was detected after white noise adaptation and then after reading text between the two refractive groups.

The first aspect of the experimental paradigm to consider is the orientation of Gabor test patches, which were set to a vertical orientation (the Metropsis default) for all measurements. This should have been sufficient to detect any $\log_{10}CS$ change at the text stroke frequency that has been purported to contain power in the vertical domain (Majaj et al., 2002). Blakemore and Nachmias (1971) suggested that horizontal adapting gratings had no influence on subsequently presented vertical gratings. Figure 2.6 likens a horizontally orientated Gabor to rows of text and inter-text space. In this experiment, it is likely that the vertically orientated test Gabor's may have been inappropriate to detect change from the horizontal text row frequency given the orientation specificity of contrast adaptation. Closer inspection of the text stimulus also revealed that the use of single-spacing meant that the height of rows of text was greater than the inter-text space that will have resulted in an inaccurate trigonometric calculation of the text-row frequency (Figure 2.7).

Contrast sensitivity measurements took an average of eight minutes for all participants, whilst the adaptation period was 30 minutes. This produces an inspection:measurement ratio of 3.75:1. Periods of adaptation "top-up," were not incorporated during post-adaptation contrast sensitivity measurements and this may have led to the dissipation of any adaptation effect. Ohlendorf and Schaeffel (2009) reported that after 10 minutes adaptation, contrast adaptation was maintained for two minutes and reached baseline after five minutes, an inspection:measurement ratio of 5:1. It is well established that recovery time increases with inspection time (Georgeson & Georgeson, 1987; Rose & Evans, 1983), but recovery time also depends on the time taken to reach saturation (Magnussen & Greenlee, 1985). The initial 30 minutes of adaptation in this study may therefore have been insufficient to produce a measureable contrast adaptation effect.

When designing the experiment, the assumption was that recovery from contrast adaptation increases with the inspection time or time to reach saturation, and that it can take up to several hours to recover to baseline levels after 30 minutes adaptation (Blakemore et al., 1970; Blakemore et al., 1973; Magnussen & Greenlee, 1985; Greenlee, Georgeson & Magnussen, 1991). Furthermore, the two alternative forced choice procedure utilised in this experiment may have further contaminated the response window when compared with a more traditional and less time-consuming threshold adjustment method (Greenlee et al., 1991). The lack of a significant contrast adaptation effect may have been a combination of

an insufficient period of initial adaptation for participants to reach saturation and a lack of adaptation top-up during contrast sensitivity measurements.

Section 2.2.3 discusses the selection of spatial frequencies measured. In this experiment, participants' refractive errors were corrected with spectacle lenses and this will have induced retinal image minification for myopes. The spatial frequencies perceived by myopic participants will thus have been higher than those actually presented thereby negating a valid comparison of contrast sensitivity between refractive error groups. Specifically, this may account for the significant difference in pre-adaptation contrast sensitivity between myopes at 19.1cdeg^{-1} (section 2.4.1). An alternative means of refractive correction should be considered in future studies, i.e. contact lenses that will not cause magnification and will ensure ocular accommodation is measured.

Presentation of adaptor and test stimuli on different screens meant that post-adaptation $log_{10}CS$ measurements could only be made once additional plus lenses and the adaptor laptop had been removed from in front of the participant, providing further opportunity for adaptation effects to dissipate. Displaying both adaptation and contrast test stimuli on the same monitor would have allowed presentation of top-up adaptation stimulus in-between the visual evaluation however this was not possible due to the monitor resolution requirements.

2.4.4 Correlations
For all participants, there was a statistically significant negative correlation at 1, 2 and 4.8cdeg^{-1} (Figure 2.12a). Lower pre-adaptation $log_{10}CS$ resulted in greater elevation of $log_{10}CS$ post-noise adaptation whilst higher pre-adaptation $log_{10}CS$ resulted in greater depression of $log_{10}CS$. This alludes to the role of previous visual experience as a factor in determining the magnitude of contrast adaptation, for example: lower pre-adaptation $log_{10}CS$ for any given spatial frequency may reflect habitual contrast sensitivity depression as a consequence of prior visual experience.

Similar negative correlations were found for all participants after text adaptation (Figure 2.13a, this time significant at the spatial frequencies corresponding to the text row spatial frequency (1 and 2cdeg^{-1}). Upon examining each refractive group, the correlation was significant for emmetropic participants but not myopes (1cdeg^{-1} $p < 0.01$ *vs.* $p = 0.73$; 2cdeg^{1} $p < 0.01$ *vs.* $p = 0.46$).

These results reveal that the spatial frequencies for which there is the greatest potential for contrast adaptation would appear to be greater at lower rather than higher spatial frequencies. This finding may relate to the height of the contrast sensitivity function at the frequencies tested in this study, with greater potential to adapt at frequencies to which the

visual system is most sensitive. It was predicted that adaptation effects would be measurable at the text row ($1.6cdeg^{-1}$) and stroke ($9.6cdeg^{-1}$) frequencies. However, greater adaptability seems to exist at the lower frequency relating to the text width. This suggests that the text row frequency may be of more importance in understanding adaptation effects to text than the stroke width.

2.5 Conclusion

No significant contrast adaptation was found after uniform white noise adaptation or after reading text on a screen in either emmetropic or myopic participants. This is most likely as a consequence of differences in the experimental design compared to extant studies for which a significant effect has been detected; specifically, only measuring contrast sensitivity with vertically orientated Gabor patches, not topping up adaptation, and presenting adaptation and measurement stimuli on different screens. Pre-adaptation contrast sensitivity measurements were comparable to other studies, however, the post-adaptation contrast sensitivity measurement protocol requires revision. Revisions should include consideration of the orientation of test gratings, adaptor stimulus inspection time *vs*. contrast sensitivity measurement time (including the use of adaptor stimuli to top up adaptation), and the testing distance for adaptation and measurement.

The lack of significant contrast adaptation makes it inappropriate to draw firm conclusions as to the capacity of a uniform white noise adaptor to modify participants' pre-adaptation contrast sensitivity. However, the statistically significant correlations do indicate the potential for adaptation at the lower spatial frequencies tested.

Chapter 3
Experiment 2: Myopes experience greater contrast adaptation during reading.

3.1 Introduction

Myopia's threat to vision throughout the world is growing (Wong et al., 2014). Near work is frequently cited as being myopigenic (Saw et al., 2001; Mutti, et al., 2002; Saw et al., 2002), and epidemiological studies have found a significant correlation between myopia rate and increasingly competitive and rigorous education systems that involve prolonged periods spent reading (see Morgan et al., 2012; Huang et al., 2015 for reviews).

Reading text may lead to contrast adaptation (Greenhouse et al., 1992; Chen et al., 2006) and section 1.8 and 1.9 discuss how contrast adaptation may have the potential to interrupt the emmetropisation process and thus be myopigenic. Section 2.4.3 addressed potential reasons why contrast adaptation was not elicited in an earlier protocol (Experiment 1). In this new study, contrast adaptation was measured following 180s of reading on-screen text in myopic and emmetropic adult participants. As in Experiment 1, the spatial frequencies corresponded to the horizontal text rows (text row frequency) and vertically to the character strokes (text stroke frequency), to ascertain whether reading altered sensitivity specifically to these spatial frequencies. In addition, contrast sensitivity was measured for the same spatial frequencies but at orthogonal orientations. These served as control stimuli, to establish whether measured effects corresponded specifically to the combined peak spatial frequencies and orientations present in the adapter stimulus.

The contrast sensitivity measurement protocol that followed the adaptation period was interspersed with 30s intervals of additional reading to "top-up" adaptation. The hypothesis was that reading would induce contrast adaptation that would result in a degraded retinal image. It has been shown that a degraded retinal image may contribute to myopia development both in animal studies (Sivak, Barrie & Weerheim, 1989; Bartmann & Schaeffel, 1994; Norton, 2016), and in humans (Robb, 1977; Hoyt et al., 1981; Rabin et al., 1981; Gee & Tabbara, 1988; Schaeffel, 2006).

3.2 Method

The following experimental design addresses the issues identified and discussed in section 2.4.3 that are thought to have lead to significant contrast adaptation effects not being detected in Experiment 1.

3.2.1 Participants

Twenty young adult participants took part, aged 19 to 34 years (mean age 24.35 ± 4.57), 10 of whom were classified as myopic (spherical equivalent refraction, sphere + ½ cylinder

[SER]) (SER > -0.75D) and 10 emmetropic (SER +0.50 to -0.25D), summarised in Table 3.1. Refractive error was determined by subjective assessment of maximum plus consistent with best visual acuity to the nearest 0.25D.

	Participant Group	
	Emmetropic	**Myopic**
Mean age (y) ± SD	21.44 ± 3.09	25.89 ± 4.26
Gender (male:female)	4:6	5:5
Mean SER ± SD (D)	0.01 ± 0.14	-2.94 ± 1.69

Table 3.1: mean age, gender and mean spherical equivalent refractive error (SER) for emmetropic and myopic participants.

Inclusion criteria were: best-corrected acuity ≤ 0.00 logMAR in each eye; monocular Pelli-Robson Chart log contrast sensitivity ≥ 1.65; SER between -5.00DS and +0.50DS; astigmatism ≤0.75DC, anisometropia ≤ 1.00D, an absence of ocular pathology and suitability for contact lens wear. All participants were fully corrected for their spherical equivalent distance correction with Biotrue ONEday soft contact lenses (Bausch & Lomb, fitting parameters: base curve 8.6mm; total diameter 14.2mm; Dk/t 42 @ centre for -3.00 and water content 78%). All tasks were performed binocularly.

Informed written consent (Appendix B) was obtained from all participants following a written (Appendix A) and verbal explanation of the experiment. Procedures were approved by the Anglia Ruskin University Faculty Research Ethics Panel, and followed the Tenets of the Declaration of Helsinki. Data were collected from each of the participants in a single session.

3.2.2 Apparatus

All stimuli were presented on a 19'' Sony Trinitron GDM-F520 CRT that was calibrated for luminance and chromaticity at the start of each session using a ColorCal colorimeter (made for Cambridge Research Systems by Minolta, Japan). Mean luminance was 50 cd/m^2. The display was 38.2 × 28.5cm, and was placed at distance 52cm from participants (who were positioned in a forehead and chin rest) and therefore subtended 36.3° × 28.7° of visual angle. At a spatial resolution of 1280 × 961, this produced 85 DPI horizontally and vertically. The viewing distance was increased slightly from Experiment 1 as a > 50cm distance to VDU screens has been reported preferable (Jaschinski-Kruza, 1990; Jaschinski-Kruza, 1991). Test gratings (see section 2.2.3) were generated using a ViSaGe visual stimulus generator, with 14-bit color and luminance control (Cambridge Research Systems Ltd, Rochester, UK). The room illumination was measured with a CEM DT1308 light meter (MeterShack, Ruby Electronics, San Jose, USA) for each participant. The average room luminance was 111cd/m^2 (range 109-115cd/m^2). The psychophysical paradigm and CRT calibration routines were implemented with MATLAB (The Mathworks Inc., Natick MA) using

the PsychToolbox extensions (Kleiner et al., 2007; Brainard, 1997; Pelli. 1997), which could test contrast sensitivity and display the adaptor stimulus. Functions from the CRS Toolbox (Cambridge Research Systems Ltd, Rochester, UK) were used for stimulus rendering.

3.2.3 Stimuli

A high-contrast text stimulus was created using an English text excerpt from the novel "The Da Vinci Code" (Transworld Publishers, London, UK), such that the maximum pixel intensity was 255 and the minimum was 127 in the range 0-255 (i.e., 8-bit grayscale). Thirty lines of text were visible on the screen at any time, with line spacing equal to the height of uppercase letters, and text was formatted as continuous prose without paragraph breaks, and filled the entire screen. The Verdana font was used as, in a study that compared a range of serif and sans serif fonts, it was found to elicit the fastest reading time and was deemed the most legible (Bernard, Lida, Riley, Hackler & Janzen, 2002). Rather than specifying text parameters by typical point size, text size, height, kerning and line spacing were reverse engineered to generate the desired row frequency ($1cdeg^{-1}$) and stroke frequency ($4cdeg^{-1}$) whilst maintaining a naturalistic appearance for reading. A sample of the text adaptor is shown in Figure 3.1.

Renowned curator Jacques Sauniere staggered through the vaulted archway of the museum's Grand Gallery. He lunged for the nearest painting he could see, a Caravaggio. Grabbing the gilded frame, the seventy-six-year-old man heaved the masterpiece toward himself until it tore from the wall and Sauniere collapsed backward in a heap beneath the canvas. As he had anticipated, a thundering iron gate fell nearby, barricading the entrance to the suite. The parquet floor shook. Far off, an alarm began to ring. The curator lay a moment, gasping for breath, taking stock. I am still alive.He crawled out from under the canvas and scanned the cavernous space for someplace to hide. A voice spoke, chillingly close. "Do not move." On his hands and knees, the curator froze, turning his head slowly. Only fifteen feet away, outside the sealed gate, the mountainous silhouette of his attacker stared through the iron bars. He was broad and tall, with ghost-pale skin and thinning white hair. His irises were pink with dark red pupils. The albino drew a pistol from his coat and aimed the barrel through the bars, directly at the curator. "You should not have run." His accent was not easy to place. "Now tell me where it is." "I told you already," the curator stammered, kneeling defenseless on the floor of the gallery. "I have no idea what you are talking about!" "You are lying." The man stared at him, perfectly immobile except for the glint in his ghostly eyes. "You and your brethren possess something that is not yours." The curator felt a surge of adrenaline. How could he possibly know this? "Tonight the rightful guardians will be restored. Tell me where it is hidden, and you will live." The man leveled his gun at the curator's head. "Is it a secret you will die for?" Sauniere could not breathe. The man tilted his head, peering down the barrel of his gun. Sauniere held up his hands in defense. "Wait," he said slowly. "I will tell you what you need to know." The curator spoke his next words carefully. The lie he told was one he had rehearsed many times... each time praying he would never have to use it. When the curator had finished speaking, his assailant smiled smugly. "Yes. This is exactly what the others told me." Sauniere recoiled. The others? "I found them, too," the huge man taunted. "All three of them. They confirmed what you have just said." It cannot be! The curator's true identity, along with the identities of his three senechaux, was almost as sacred as the ancient secret they protected. Sauniere now realized his senechaux, following strict procedure, had told the same lie before their own deaths. It was part of the protocol. The attacker aimed his gun again. "When you are gone, I will be the only one who knows the truth." The truth.In an instant, the curator grasped the true horror of the situation. If I die, the truth will be lost forever.Instinctively, he tried to scramble for cover. The gun roared, and the curator felt a searing heat as the bullet lodged in his stomach. He fell forward... struggling against the pain. Slowly, Sauniere rolled over and stared back through the bars at his attacker. The man was now taking dead aim at Sauniere's head. Sauniere closed his eyes, his thoughts a swirling tempest of fear

Figure 3.1: A sample of the high-contrast text adaptor stimulus. 30 lines of text were visible at all times.

The spatial frequency created by text rows in the stimulus was calculated by trigonometry as shown in Figure 3.2. Where screen height h = 28.5cm, and the distance to the screen

from the observer d = 52cm, the angle of elevation from the observer, measured in degrees, was given by $\tan^{-1}(h \div d) = 28.72°$. Since the stimulus comprised 30 rows of text, spanning the entire vertical extent of the screen, the angle subtended by a single cycle of text (which was defined as a row of text and the following inter-text row of blank space) was $28.72 \div 30 = 0.96$ cdeg^{-1} (i.e., $\approx$ 1cdeg^{-1}).
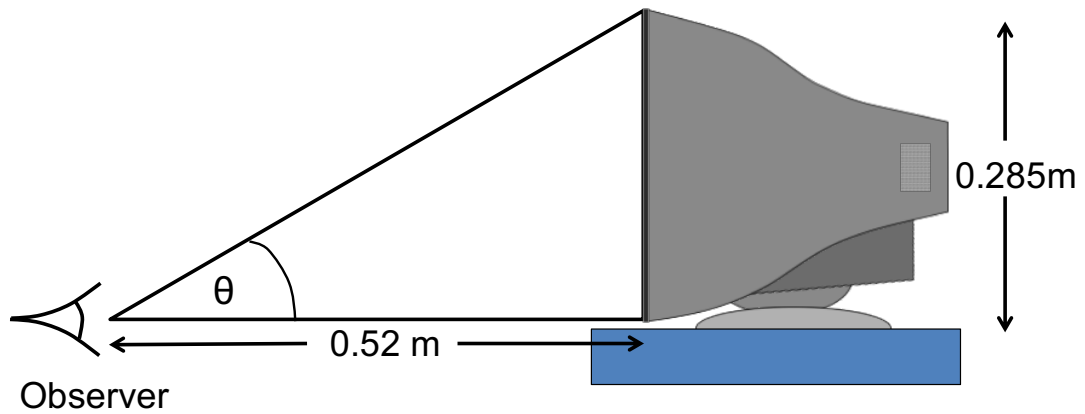
Figure 3.2: Trigonometric calculation of text row frequency calculated from screen height.

The stroke frequency was calculated using the method described in Majaj et al. (2002), illustrated in Figure 2.8 in which it is suggested that the stroke frequency created by letters is the sole determinant of the channel frequency utilised by an observer in their neural perception of a letter. To account for the unjustified right edge of text, a straight edge was used to divide the screen in half vertically. A horizontal line was drawn through a row of text at half the height of a lower case letter and the number of vertical strokes crossing this line were counted and repeated for first 30 rows of text. Average stroke frequency was calculated by dividing the average number of strokes across all rows by half the horizontal screen size in degrees to give a stroke frequency of 3.96 ± 0.47 (mean ± SD) strokes per degree. Once a page of text had been read, participants pressed a button to advance to a new page of text, with similar stroke frequency characteristics, to help maintain interest and concentration (see section 3.2.4 below).

Contrast sensitivity was measured for 1cdeg^{-1} and 4cdeg^{-1} using Gabor test gratings orientated at both 90° (vertical) and 0° (horizontal), and subtended 2.35° visual angle at the screen distance of 52cm.

3.2.4 Procedure

A QUEST two-alternative forced choice (2AFC) procedure was selected (as discussed in section 2.2.5.1), wherein participants were requested to a press a button on the CB6 push button response box (Figure 2.1) to indicate whether a grating appeared to the left or right of a central fixation target. Stimuli were presented for 300ms, using a raised cosine temporal envelope. The termination criterion was set at a confidence interval of 95% and a white circle (size 0.2°) was displayed at the screen centre as a fixation target. The contrast sensitivity test protocol was explained to participants, who were then given the opportunity to practice until confident with their comprehension of the procedure. Pre-adaptation contrast sensitivity measurements were recorded for Gabor test gratings of $1cdeg^{-1}$ and $4cdeg^{-1}$ at both 90° and 0° orientations. One staircase for each stimulus orientation/frequency setting was run, with trials for each of these four conditions interleaved randomly, terminating at convergence.

The $1cdeg^{-1}$ horizontal grating matched the "row frequency," of the text whilst the $4cdeg^{-1}$ matched its vertical "stroke frequency," (Majaj et al., 2002). The orthogonally orientated ($1cdeg^{-1}$ vertical and $4cdeg^{-1}$ horizontal) Gabors acted as corresponding controls for the two frequencies derived from the text stimuli. Three pre-adaptation measurements of contrast sensitivity were obtained at each spatial frequency and orientation, the average of which was taken as the pre-adaptation contrast sensitivity. Following the three pre-adaptation contrast sensitivity measurements, participants read the text continuously for 180s, after which post-adaptation contrast sensitivity measurement was automatically started.

The post-adaptation measurements used a "top-up" procedure whereby after 15s (five trials) of testing contrast sensitivity, the text adaptor was automatically displayed for 30s of reading, after which contrast sensitivity testing recommenced for another 15s followed by 30s text top-up until the staircase was completed for each of the four test conditions. Gabor patches for contrast sensitivity measurement were displayed on the same screen as the text adaptor, thereby negating the need for any re-fixation or head movement. An audible beep denoted the commencement of the contrast sensitivity measurement. This seamless alternation between text adaptor and contrast sensitivity measurement facilitated rapid, smooth switching between the two tasks, thereby minimising any loss of adaptation during the transition and avoiding the need to accommodate at different distances.

3.2.5 Analysis

Contrast thresholds were recorded as the common logarithm of the reciprocal of the threshold contrast, i.e. log contrast sensitivity ($\log_{10}CS$). A 2×2×2×2 mixed ANOVA was conducted where $\log_{10}CS$ was the dependent variable. The first within subjects factor was

adaptation with two levels (pre-adaptation and post-text adaptation). The second within subjects factor was spatial frequency with two levels, (1 and 4cdeg^{-1}). The third within subjects factor was orientation with two levels (horizontal and vertical). The between subjects factor was participant group, with two levels (myopic and emmetropic).

3.3 Results

3.3.1 Pre-adaptation contrast sensitivity

Contrast sensitivity measurements were found to be reliable: the coefficient of variation (COV) was calculated for the pre-adaptation $\log_{10}$CS values for each subject, and for each spatial frequency, to determine the repeatability of the measurements. The standard deviation of each participant's three pre-adaptation $\log_{10}$CS measurements was divided by the mean of the three $\log_{10}$CS values to give the COV. The mean COV for all participants and spatial frequencies was 3.57% (when COV is expressed as a percentage it is the relative standard deviation) (range: 0.52-12.85%), well within the acceptable range defined by Lesmes, Lu, Baek & Albright, (2010). There was no significant difference in pre-adaptation $\log_{10}$CS between refractive error groups independent samples t-tests: 1cdeg^{-1} vertical $t_{(18)}$ = -0.36; p = 0.72 (two-tailed); 1cdeg^{-1} horizontal $t_{(18)}$ = -1.63; p = 0.12 (two-tailed); 4cdeg^{-1} vertical $t_{(18)}$ = -0.82; p = 0.43 (two-tailed); 4cdeg^{-1} horizontal $t_{(18)}$ = -1.40; p = 0.19 (two-tailed).

3.3.2 Post-adaptation contrast sensitivity

Figure 3.3 and Table 3.2 show mean pre-adaptation and post-text adaptation $\log_{10}$CS when measured with both horizontal and vertical test gratings at 1cdeg^{-1} and 4cdeg^{-1} for all participants (left), emmetropic participants (centre) and myopic participants (right). Significant main effects of adaptation [Wilks' Lambda = 0.54; $F_{(1,18)}$ = 15.07, p < 0.01, η_p^2 = 0.46] and spatial frequency were found [Wilks' Lambda = 0.54; $F_{(1,18)}$ = 15.47, p < 0.01, η_p^2 = 0.46]. There were significant interactions between adaptation, spatial frequency and orientation [Wilks' Lambda = 0.62; $F_{(1,18)}$ = 11.15, p < 0.01, η_p^2 = 0.38], and adaptation, spatial frequency and participant group [Wilks' Lambda = 0.75; $F_{(1,18)}$ = 5.92, p = 0.03, η_p^2 = 0.25]. Separate statistical analyses were therefore conducted to investigate the effects of individual factors on logCS.

3.3.3 Contrast adaptation

A mixed between-within participants ANOVA was conducted to compare $\log_{10}$CS before and after reading (i.e., adaptation) in myopic and emmetropic participants for each spatial frequency and orientation (Table 3.3). For 1cdeg^{-1} horizontal, there was a significant adaptation effect [Wilks' Lambda = 0.33; $F_{(1,19)}$ = 36.61, p < 0.01, η_p^2 = 0.67], with both refractive error groups showing reduced $\log_{10}$CS after reading (Table 3.3). The adaptation

effect was only marginal at the text stroke frequency [4cdeg^{-1} vertical: Wilks' Lambda = 0.85; $F_{(1,19)}$ = 3.30, p = 0.09, η_p^2 = 0.16] and there was no adaptation effect at the orthogonal control frequencies.
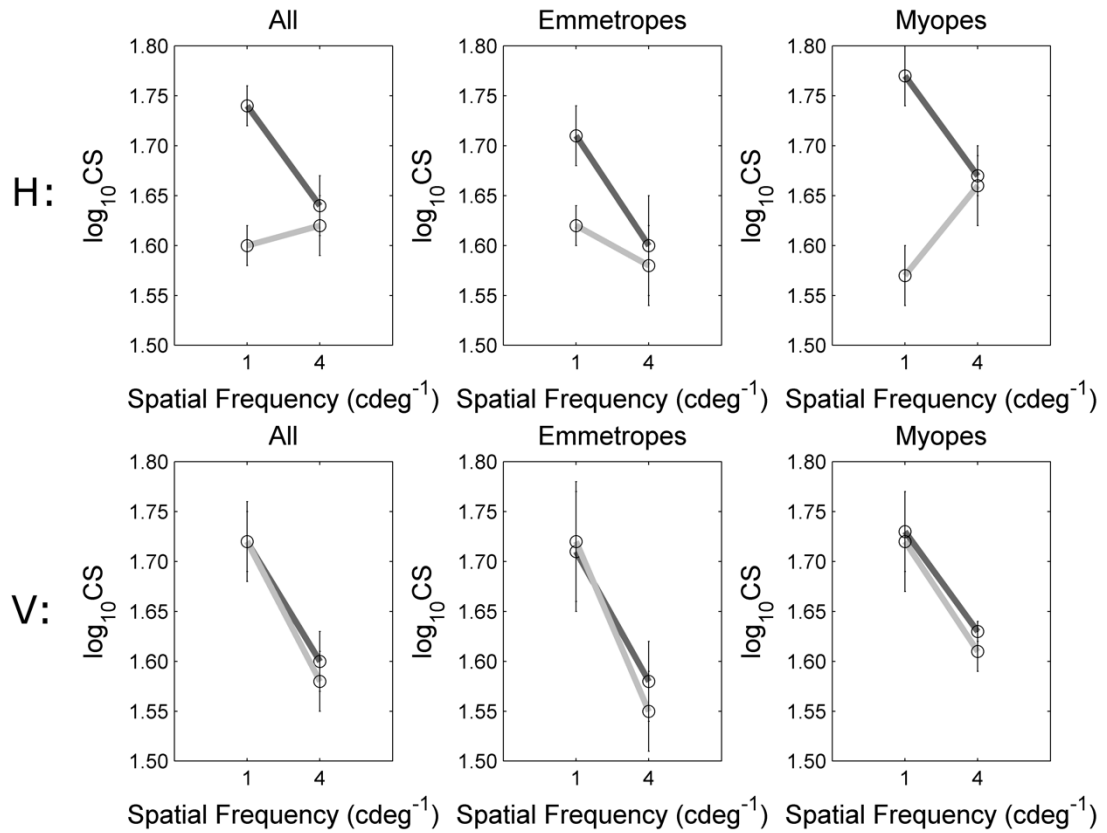
Figure 3.3: Mean pre-adaptation (dark line) and post-adaptation (light line) log$_{10}$CS for horizontal (H: upper row) and vertical (V: lower row) test gratings for all participants (left), emmetropes (centre) and myopes (right). Error bars show ± 1 SEM.

Spatial Frequency	Orientation	Participant Group					
		All		Emmetropic		Myopic	
		Pre	Post	Pre	Post	Pre	Post
$1cdeg^{-1}$	H	1.74 ± 0.02	1.62 ± 0.02	1.71 ± 0.03	1.62 ± 0.02	1.77 ± 0.03	1.57 ± 0.03
	V	1.72 ± 0.03	1.72 ± 0.04	1.71 ± 0.04	1.72 ± 0.06	1.73 ± 0.04	1.72 ± 0.05
$4cdeg^{-1}$	H	1.64 ± 0.03	1.62 ± 0.03	1.60 ± 0.05	1.58 ± 0.04	1.67 ± 0.02	1.67 ± 0.01
	V	1.61 ± 0.03	1.58 ± 0.03	1.58 ± 0.05	1.55 ± 0.05	1.63 ± 0.02	1.61 ± 0.02

Table 3.2: Mean $\log_{10}CS$ values pre and post text adaptation ± 1 SEM (log unit) for each spatial frequency and orientation tested (H: Horizontal; V: Vertical).

Spatial frequency	Orientation	Wilks' Lambda	$F_{(1,19)}$	p	η_p^2
$1cdeg^{-1}$	V	1.00	< 0.01	0.98	< 0.01
	H	0.33	36.61	< 0.01	0.67
$4cdeg^{-1}$	V	0.85	3.30	0.09	0.16
	H	0.99	0.20	0.66	0.01

Table 3.3: Results of mixed model ANOVA to determine adaptation effects at each spatial frequency and orientation tested.

Contrast adaptation was defined as the magnitude of change in $\log_{10}CS$ pre-post text adaptation (Figure 3.4 and Table 3.4).
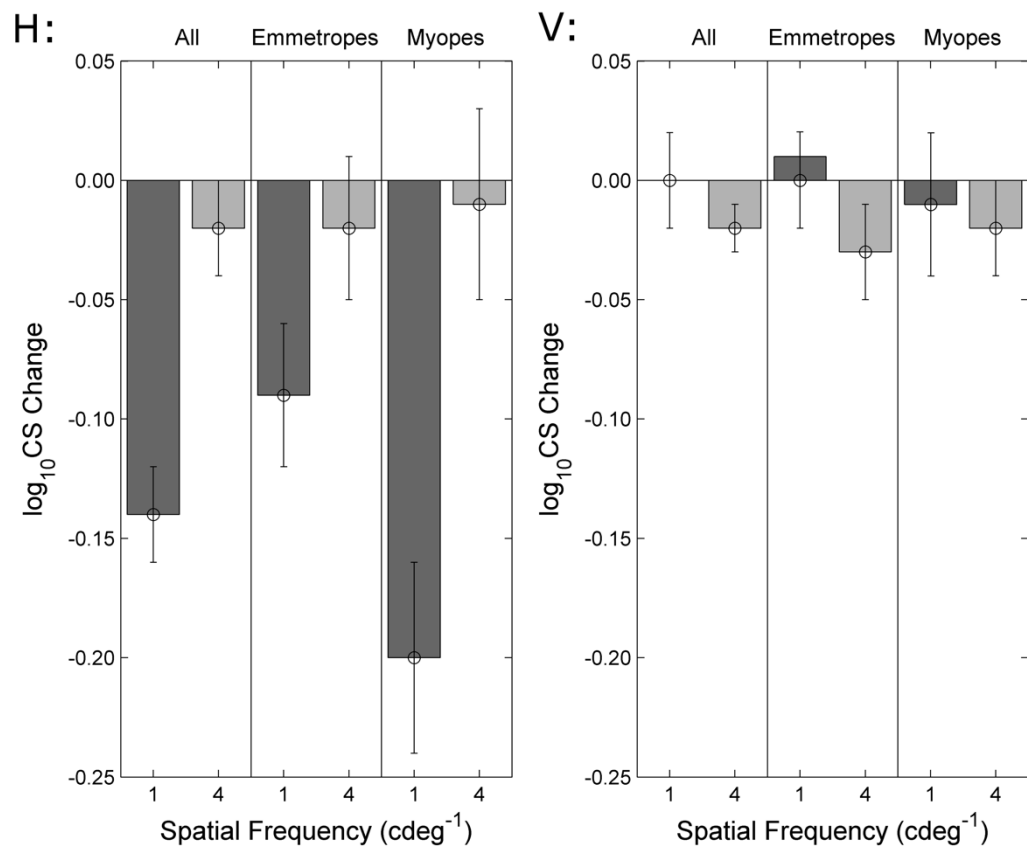
Figure 3.4: $\log_{10}CS$ change (contrast adaptation) after text adaptation for horizontal (H) and vertical (V) test gratings for all participants, emmetropes and myopes. Error bars show ± 1 SEM.

Spatial Frequency	Orientation	Participant Group		
		All	Emmetropic	Myopic
$1cdeg^{-1}$	H	-0.14 ± 0.02*	-0.09 ± 0.03*	-0.20 ± 0.04*
	V	0.00 ± 0.02	0.01 ± 0.02	-0.01 ± 0.03
$4cdeg^{-1}$	H	-0.02 ± 0.02	-0.02 ± 0.03	-0.01 ± 0.04
	V	-0.02 ± 0.01	-0.03 ± 0.02	-0.02 ± 0.02

Table 3.4: log contrast adaptation ± 1 SEM (log unit) (post-adaptation $\log_{10}CS$ – pre-adaptation $\log_{10}CS$) values for all participants, emmetropes and myopes for each test grating. *denotes contrast adaptation significant at $p \leq 0.05$.

Spatial Frequency	Orientation	Participant Group					
		All		Emmetropic		Myopic	
		$t_{(19)}$	p	$t_{(9)}$	p	$t_{(9)}$	p
$1cdeg^{-1}$	H	5.38	< 0.01*	2.66	0.03*	5.76	< 0.01*
	V	0.02	0.98	-0.30	0.77	0.27	0.80
$4cdeg^{-1}$	H	0.46	0.65	0.47	0.65	0.18	0.86
	V	1.83	0.08	1.76	0.11	0.75	0.47

Table 3.5 Results of paired *t*-tests comparing mean pre- and post-adaptation $\log_{10}CS$ for each spatial frequency and for all participants, emmetropes and myopes. *denotes significant difference in $\log_{10}CS$ pre-post adaptation at $p \leq 0.05$.

Paired *t*-tests were conducted to compare pre and post text adaptation $\log_{10}CS$ (Table 3.5) and showed a statistically significant reduction in $\log_{10}CS$ post text adaptation at the text row frequency (1cdeg^{-1} horizontal) [$t_{(19)}$ = 5.38; p < 0.01] but only a marginal effect at text stroke frequency (4cdeg^{-1} vertical) $t_{(19)}$ = 1.83; p = 0.08. When split by refractive error group, the reduction in $\log_{10}CS$ at 1cdeg^{-1} horizontal was significant for both emmetropes [$t_{(9)}$ = 2.66; p = 0.03] and myopes [$t_{(9)}$ = 5.76; p < 0.01]. Independent samples *t*-test compared the magnitude of contrast adaptation between refractive error groups (Table 3.6). Myopic participants showed significantly greater adaptation, roughly twice as much, compared to emmetropic participants (0.20 ± 0.04 log units *vs*. 0.12 ± 0.04 log units) [$t_{(18)}$ = 2.31; p = 0.03 (two-tailed)].

Spatial frequency	Orientation	$t_{(18)}$	p
1cdeg^{-1}	H	2.31	0.03*
	V	0.41	0.67
4cdeg^{-1}	H	-0.27	0.78
	V	-0.75	0.47

Table 3.6: Independent samples *t*-tests comparing magnitude of mean contrast adaptation between emmetropic and myopic participants for each spatial frequency and orientation.

For all participants, there was no significant change in $\log_{10}CS$ pre-post text adaptation at the orthogonal control spatial frequencies of 1cdeg^{-1} vertical [paired t-test $t_{(19)}$ = 0.24; p = 0.98], or 4cdeg^{-1} horizontal [paired t-test $t_{(19)}$ = 0.46; p = 0.65]. Furthermore, there was no significant difference in the magnitude of contrast adaptation between the refractive groups at 1cdeg^{-1} vertical [independent samples t-test $t_{(18)}$ = 1.07; p = 0.30 (two-tailed)] or at 4cdeg^{-1} horizontal [independent samples t-test $t_{18)}$ = -0.10; p = 0.92 (two-tailed)].

3.4 Discussion

Consistent with earlier studies (Lunn & Banks, 1986; Magnussen et al., 1992; Greenhouse et al., 1992), reading text displayed on a computer screen produced significant contrast adaptation. Additionally, myopes exhibited significantly greater contrast adaptation than emmetropes at the lower spatial frequency. This is in agreement with Yeo et al. (2012), in which significant contrast adaptation was found in children after reading a page of printed text. Moreover, the results of this experiment show adaptation effects at the text row frequency (1cdeg^{-1} horizontal), but not at the text stroke frequency (4cdeg^{-1} vertical), with no contrast adaptation for the orthogonal control frequencies.

3.4.1 Contrast adaptation at the text row frequency

Contrast adaptation at 1cdeg^{-1} was greater for myopic participants (0.20 log units) than emmetropic participants (0.09 log units). Yeo et al. (2012) were the first to demonstrate greater contrast adaptation in myopes than emmetropes after reading printed text. Their

emmetropic participants showed significant contrast adaptation at 2.7cdeg^{-1}, which was not one of the dominant spatial frequencies present in their text target. Furthermore, amongst their myopic participants, the text row and stroke frequencies did not show the greatest magnitude of adaptation of the five spatial frequencies tested. The observed pattern of reduced sensitivity at all tested frequencies and the greatest sensitivity depression at spatial frequencies unrelated to text leave open the possibility that some processes besides adaptation may have contributed to reported group differences. Direct comparison with the study of Yeo et al. (2012) is complicated by the use of different participant groups (children *vs*. adults) and stimuli.

Figure 1.8 illustrates that grating adaptation reduced log$_{10}$CS up to 0.50 log units at the adaptation frequency whilst contrast sensitivity was enhanced by approximately 0.10 log units (1/5th as much) two octaves away. In the current study, the greatest magnitude of contrast adaptation was 0.20 log units for myopic observers at 1cdeg^{-1}. The lower level of adaptation is consistent with the finding that simultaneous multiple spatial frequency channel adaptation results in a smaller loss in contrast than from individually stimulated spatial frequency channels (Greenlee & Magnussen, 1988; Yeo et al., 2012). Contrast sensitivity was measured two octaves away at 4cdeg^{-1} (in this instance to act as a control): any anticipated enhancement of contrast sensitivity at this frequency could only have been expected to be in the region of 0.04 log units (1/5th of the adaptation effect measured at the fundamental frequency) and accordingly, no contrast adaptation was measured at this frequency.

The present study has shown contrast adaptation specific to the frequency and orientation of text rows for both participant groups, and that adaptation was significantly greater in myopic participants. This result suggests that there may be a fundamental difference in adaptation susceptibility between the two refractive error groups, implicating this spatial frequency as potentially important. This is a tentative claim and any suggestions that this may be a causal factor requires further study; however, the relationship between near work and myopia development (Saw et al., 2001; Mutti et al., 2002; Saw et al., 2002) does support this postulation.

The specificity of adaptation as demonstrated by a significant change in log$_{10}$CS at 1cdeg^{-1} using a horizontally oriented Gabor, coupled with no effect at the control frequency of 1cdeg^{-1} using a vertically orientated Gabor, highlights the role of the text row frequency in inducing contrast adaptation during reading. It section 2.4.4, the correlation between contrast sensitivity post-text adaptation and the amount of contrast adaptation is discussed. It was hypothesised that the text row frequency may be of more importance in understanding

adaptation as there was no measured adaptation at the text stroke frequency. The results presented in this study would support this suggestion.

Greater contrast adaptation was found in this study than in the study of Yeo et al. (2012), which may be due to a more robust experimental paradigm that incorporates a top-up procedure, and the use of a single display screen for adaptation and contrast sensitivity testing (eliminating differences attributable to accommodative lag) but could also potentially be a consequence of this study's binocular adaptation and contrast sensitivity measurements, compared with their binocular adaptation and monocular contrast sensitivity measurements.

3.4.2 Lack of contrast adaptation at the text stroke frequency
The results of the mixed ANOVA in Table 3.3 suggest only a weak adaptation effect at the text stroke frequency. Majaj et al. (2002) suggested that the stroke frequency of letters is a viable predictor of their central spatial frequency along the horizontal meridian. Having not shown contrast adaptation at the stroke frequency of 4cdeg^{-1}, a Fast Fourier Transform (FFT) was applied to an image containing the text adaptor to test this assumption.

Figure 3.5 (A-C) illustrate how the text stimulus was processed to obtain an FFT that represents vertical power (created by horizontal text rows), by taking vertical samples through the image through each of the 30 text lines (A-B, shown as an average pixel intensity profile in C, wherein red shows the average of the 30 vertical samples, and blue all vertical columns through the image). Figure 3.5 (D) shows the FFT, with peak power observed at 30 whether using the 30 vertical columns (red), or all columns (blue). This equates to 30 cycles across the entire image, wherein one cycle is a row of text and the subsequent inter-text blank row. Peak power vertically, created by horizontal rows of text, was therefore the FFT max pixels ÷ vertical visual angle (30 ÷ 28.7) = 1.07cdeg^{-1}, as expected.
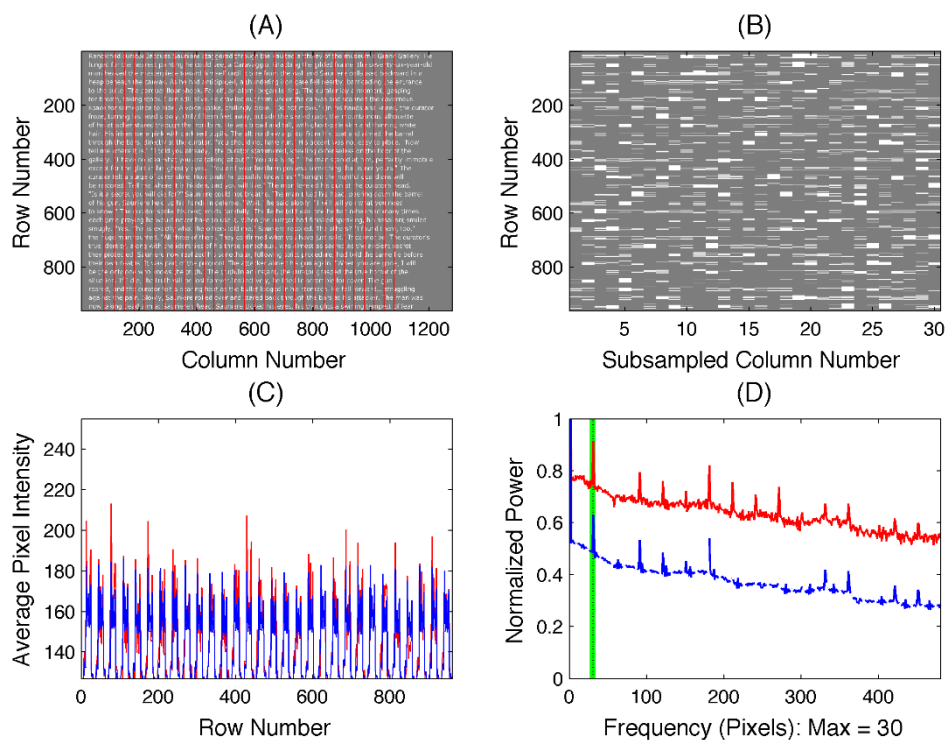
Figure 3.5: Analysis of text stimulus vertical power (A) Acquisition of stimulus subsample (30 columns, red lines); (B) Stimulus subsample; (C) Average pixel intensity profile following column averaging (blue: all columns, red: 30 column samples); (D) Average of 1-D FFTs (blue: all columns, red: 30 column samples). Green vertical line shows peak power.

Figure 3.6 shows the same analysis applied in the horizontal meridian, as created by the character strokes, and reveals a rather less distinct peak in power than the vertical meridian (above), indicating that power is distributed over a relatively wide range of horizontal frequencies. The 30 subsamples taken were aligned precisely with the centre of each row of text, and therefore captured character strokes in a manner similar to the stroke counting technique used in earlier work. The apparent lack of distinct peak(s), c.f. vertical FFT, is most likely a result of spatial uncertainty: characters start in different positions horizontally and the character strokes are not always vertical (e.g. Q, S, W). This creates a wider band peak in the FFT, causing the distribution of power across a larger number of frequencies, and reduces the overall power at each specific frequency in this band. Variation in letter shape would also distribute the power across different orientations, in comparison to the more uniform alternating rows of text and inter-row spaces, which are always in the same position and create a saw-tooth average intensity profile (Figure 3.6C). It is also apparent that, if all rows are used rather than just 30 rows aligned with the centre of each line of characters, the FFT is considerably less organized. There may thus have been insufficient power at 4cdeg^{-1} to induce contrast adaptation. Peak power in the horizontal FFT was found to be $192 \div 36.3 = 5.29\text{cdeg}^{-1}$, which is somewhat higher than the 4cdeg^{-1} suggested by the stroke counting technique (Figure 2.8), drawing into question the efficacy of that approach.
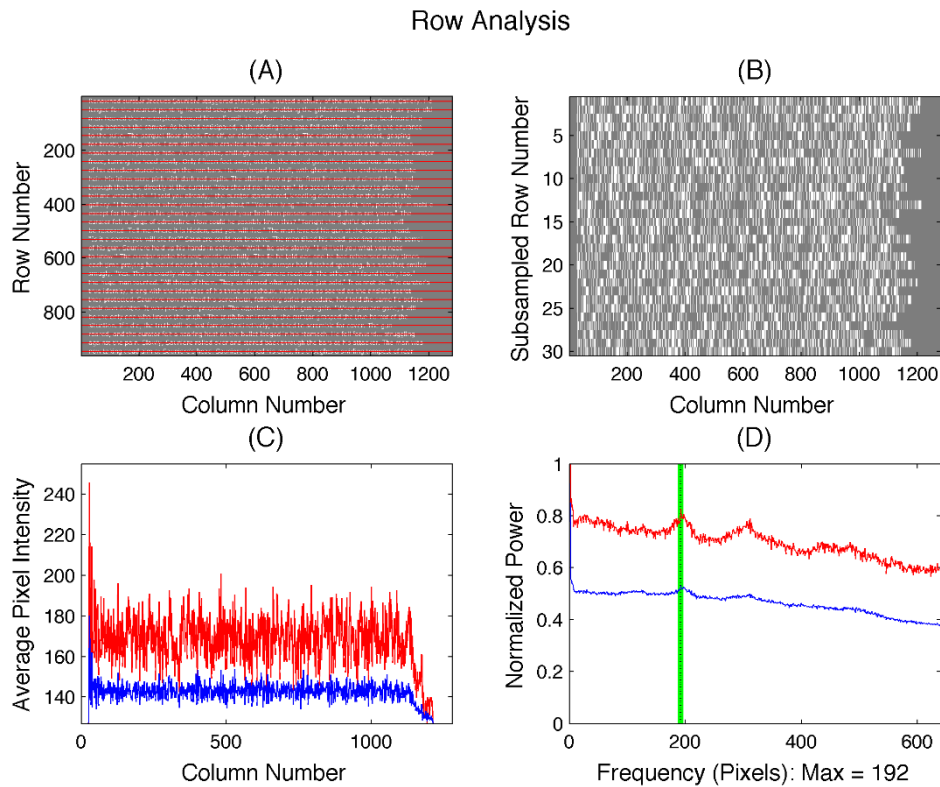
Figure 3.6: Analysis of text stimulus horizontal power. (A) Acquisition of stimulus subsample 30 rows; (B) Stimulus subsample; (C) Average pixel intensity profile following row averaging (blue: all rows, red: 30 row samples); (D) Average of 1-D FFTs (blue: all rows, red: 30 row samples). Green vertical line shows peak power.

3.4.3 Contrast adaptation and myopia

Contrast adaptation has been postulated as an error signal for emmetropisation as a consequence of altered sensitivity in the visual system with defocused stimuli (Diether et al., 1997; Diether & Schaeffel, 1997; Diether & Schaeffel, 1999). In Deither et al. (2001) it was suggested that contrast adaptation is a retinal error signal for ocular growth and myopia development. This was shown by correlating contrast adaptation in chicks with myopia onset induced by form deprivation (using frosted occluders and negative lenses) with low-pass filtered video clips. Furthermore, recovery from contrast adaptation resulted in retraction of myopia in the chicks. Animal studies propose that intermediate spatial frequencies may influence the emmetropisation process (Schaeffel, Weiss & Seidel, 1999; Schmid & Wildsoet, 1997). Schmid & Wildsoet (1997) proposed that a lack of mid-spatial frequencies in text might be responsible for stimulating myopia. Fourier analysis of the text also showed a distinct lack of mid-spatial frequency (the peak mid spatial frequency detected was 5.29cdeg^{-1}, which correlated with the letter stroke frequency but contained very little power). In future experiments, spatial frequencies to be measured pre- and post-adaptation could more reliably be derived from Fourier analysis of adaptor stimuli, rather than using stroke counting.

Animal models have shown reduced firing of cortical neurons during contrast adaptation

(Movshon & Lennie, 1979; Albrecht et al., 1984). Yeo et al. (2012) proposed that a concurrent reduction in the neural response gain may result in the perception of a defocussed retinal image, similar to the effect of translucent diffusers which degraded retinal image quality and promoted myopia development in animals (Sivak et al., 1989; Bartmann and Schaeffel, 1994). In humans, even very minor changes in retinal image quality have been related to myopia development (Robb, 1977). Mon Williams et al. (1998) reported that a change in contrast sensitivity of 0.1 log unit is clinically significant, given that the contrast sensitivity function is normally stable (Woods, Bradley & Atchison, 1996). Smith and Hung (2000) showed that the degree of image degradation required to induce deprivation myopia in monkeys was relatively low; specifically, a 0.10 $\log_{10}$CS reduction at low spatial frequencies, up to an average of 0.75 log unit reduction at higher spatial frequencies. The results in this chapter show a similar reduction in $\log_{10}$CS at 1cdeg^{-1} horizontal in all participants, but more importantly, myopic participants showed significantly greater adaptation than emmetropes.

Previous studies have postulated that contrast adaptation may be induced by accommodative inaccuracies resulting from re-fixation between adaptor and test stimuli presented at different distances (Yeo et al., 2012). This is of particular significance, given that re-fixation could induce accommodative lag and myopes have been reported to exhibit greater lags than emmetropes (Yeo et al., 2006; Abbott et al., 1998; Gwiazda et al., 1993b; McBrien & Millodot, 1986). The present study has the advantage that all adaptor and test stimuli were displayed on the same screen, and so accommodative lag and potential near-induced transient myopia resulting from re-fixation can be discounted as contributing factors in observed contrast adaptation effects.

Furthermore, the experimental setup facilitated the presentation of top-up images. In Experiment 1, contrast sensitivity was measured before and after a period of 30 minutes reading without topping up, but showed no significant contrast adaptation at either the text stroke or row frequencies. Ohlendorf and Schaeffel (2009) reported that after 10 minutes adaptation, contrast adaptation was maintained for two minutes and reached baseline after five minutes. It is well established that recovery time increases with inspection time (Rose & Evans, 1983; Magnussen & Greenlee, 1985; Georgeson & Georgeson, 1987); however, in Chapter 2, contrast sensitivity measurement took approximately eight minutes. Given Ohlendorf and Schaeffel's (2009) explanation of a 5:1 inspection to measurement time ratio, this should have been sufficient to measure a contrast adaptation effect, yet no effect was found. Having utilised a top-up procedure in the present study, the necessity to top up adaptation is highlighted.

3.5 Conclusion

To summarise, reading text on a CRT induced contrast adaptation corresponding to the spatial frequency of horizontal rows of text in young adults. Myopic participants incurred more than twice the adaptation of emmetropes. Failure to induce contrast adaptation at the text stroke frequency implies that, despite having been used in earlier work, this may not be an appropriate surrogate for the stroke spatial frequency, evidenced by the lack of a pronounced narrow-band correlate in the FFT power spectrum and mismatch between FFT analysis and stroke counting results, or that stroke frequency simply carries insufficient or insufficiently concentrated power to educe adaptation effects. The greater contrast experienced by myopes at the text row frequency after reading warrants further investigation to better understand the relationship between near work and myopia development.

Chapter 4

Experiment 3: Adaptation to a phase-randomised, but frequency, orientation, luminance, and contrast-matched text stimulus.

4.1 Introduction

Emerging evidence suggests that the magnitude of contrast adaptation to text stimuli may be larger in myopic than emmetropic observers (Yeo et al., 2012; McGonigle et al., 2016). An adaptor stimulus that was matched in spatial frequency and orientation, but randomised in phase, relative to a corresponding text stimulus, was generated. This enabled the mechanisms that underpin contrast adaptation in reading to be examined. In particular, the relative importance of stimulus cognition *vs*. the fundamental statistical properties of the adaptor were examined. The regular text stimulus was readable, but the phase randomised stimulus had the superficial appearance of text (and numerically, had identical power at each frequency-orientation band, and was matched in mean luminance and contrast), but was otherwise incomprehensible. This approach was selected over the use of phonetically valid nonsense words, since these are still 'readable', and would, like regular text, recruit high-level processing. Furthermore, such a stimulus would be nearly impossible to generate with an exact spatial frequency-orientation match to the regular text comparator stimulus.

Epidemiological studies in developed countries correlate higher rates of myopia with increasingly competitive and rigorous education systems (Goldschmidt, 1968; Wong et al., 1993; Wang et al., 1994; Wensor et al., 1999; Saw et al., 2001a; Saw et al., 2001b, Shimizu et al., 2003; Williams & Hammond, 2014), and specifically to prolonged periods of near work (Angle & Wissman, 1980; Zylbermann et al., 1993; Kinge et al., 2000; Saw et al., 2002; Mutti et al., 2002; Huang et al., 2015), and to the distance at which close work is undertaken (Ip et al., 2008). Higher intelligence quotient (IQ) has also been linked to children with myopia (Mutti et al., 2002; Saw et al., 2004). Reading is integral to each of these myopigenic environmental risk factors, and so it is important to better understand the neural processes that mediate this relationship.

It may be that greater attention elicited from active reading would educe greater contrast adaptation. Pestilli et al. (2007) found that whilst adaptation can reduce stimulus salience (see section 1.5.6), attention can increase it. Although the effect of attention is independent of the adaptation state of the system (Pestilli et al., 2007), sustained attention strengthens the magnitude of contrast adaptation (Ling & Carrasco, 2006). Extant animal (Sivak et al., 1989; Bartmann & Schaeffel, 1994) and human (Robb, 1977; Hoyt et al., 1981; Rabin et al., 1981; Gee & Tabbara, 1988; Schaeffel, 2006) studies have postulated that degraded retinal images resulting from contrast adaptation serve as an error signal for emmetropisation, and

consequently the development of myopia (Diether, & Schaeffel, 1997; Diether & Schaeffel, 1999; Diether et al., 1999).

In Chapter 3, contrast adaptation during reading was found to be significant at the text row frequency (producing power in the vertical meridian), but not at the letter stroke frequency, and to be significantly greater in myopic participants compared to emmetropic participants. Using a new participant group, for which a frequency and orientation matched stimulus was used in place of a text adaptor, this study aimed to establish whether the adaptation effects observed with text stimuli are attributable to fundamental statistical properties (*viz.*, spatial frequency and orientation), or result from higher-level cognitive processes that derive more circuitously from the 'readability' of the stimulus. It was therefore hypothesised that a near task of lower cognitive demand requiring less attention from observers would result in lower levels of contrast adaptation.

4.2 Methods

The experimental paradigm was identical to that described for Experiment 2 (section 3.2), except that a new adaptor stimulus was used. Some aspects of the experimental procedure are therefore only described in brief below.

4.2.1 Participants

Twenty young adult participants took part, aged 18 to 34 years (mean age 23.67 ± 4.27), 10 of whom were classified as myopic (SER > -0.75D; mean ± SD: -2.94 ± 1.69D) and 10 emmetropic (SER +0.50 to -0.25D; 0.01 ± 0.14D). The participants in each group are summarized in Table 4.1. Six of these emmetropic and five myopic participants also completed experiment 2.

	Participant Group	
	Emmetropic	**Myopic**
Mean age (y) ± SD	23.7 ± 5.19	25 ± 4.03
Gender (male:female)	7:3	4:6
Mean SER ± SD (D)	0.01 ± 0.14	-2.78 ± 1.40

Table 4.1: mean age, gender and mean spherical equivalent refractive error (SER) for emmetropic and myopic participant groups.

Refractive error was determined by subjective assessment of maximum plus consistent with best visual acuity to the nearest 0.25D. Inclusion criteria were: best-corrected acuity ≤ 0.00logMAR in each eye; monocular Pelli-Robson Chart log contrast sensitivity ≥ 1.65, spherical equivalent refraction (SER) ≤ -5.00DS SER ≤ +0.50DS; astigmatism ≤0.75DC, anisometropia ≤ 1.00D, an absence of ocular pathology and suitability for contact lens wear. All participants were fully corrected for their spherical equivalent distance correction with

Biotrue ONEday soft contact lenses (Bausch & Lomb, fitting parameters: base curve 8.6mm; total diameter 14.2mm; Dk/t 42 @ centre for -3.00 and water content 78%). Participants were habitual contact lens wearers, having worn contact lenses for at least one year. Lenses were inserted 30 minutes prior to the commencement of contrast sensitivity measurements to allow participants to become accustomed to these particular lenses. Over refraction and visual acuity measurements were made to confirm refraction inclusion criteria were met whilst contact lenses were worn. Participants were requested to report any discomfort, dryness or irritation whilst wearing the lenses. All tasks were performed binocularly.

Informed written consent (Appendix B) was obtained from all participants, following an explanation of the experiment. Procedures were approved by the University ethics panel, and followed the tenets of the Declaration of Helsinki. Data were collected from all participants in one session.

4.2.2 Apparatus

All stimuli were presented on a 19'' Sony Trinitron GDM-F520 CRT, for which the display parameters were identical to those described in section 3.2.2. The display was calibrated for luminance and chromaticity at the start of each session using a ColorCal colorimeter (made for Cambridge Research Systems by Minolta, Japan). Contrast sensitivity test gratings (see section 4.2.3) were generated using a ViSaGe visual stimulus generator (Cambridge Research Systems Ltd, Rochester, UK). The room illumination was measured with a CEM DT1308 light meter (MeterShack, Ruby Electronics, San Jose, USA) for each participant. The average room luminance was 111cd/m^2 (range 109-115cd/m^2). The psychophysical paradigm and CRT calibration routines were implemented with MATLAB (The Mathworks Inc., Natick MA) using the PsychToolbox/VideoToolbox extensions (Kleiner et al., 2007; Brainard, 1997; Pelli, 1997), which could test contrast sensitivity and display the adaptor stimulus. Functions from the CRS Toolbox (Cambridge Research Systems Ltd, Rochester, UK) were used for stimulus rendering.

4.2.3 Stimuli

A phase randomised adaptor was generated from the text adaptor used in Experiment 2 (Figure 4.1) in MATLAB. It shared the same spatial frequency and orientation distribution (Figure 4.2). Mean luminance (Eq. 1), Michelson contrast (Eq. 2) and RMS Contrast (Eq. 3) were matched between the original text and phase randomised text stimuli.
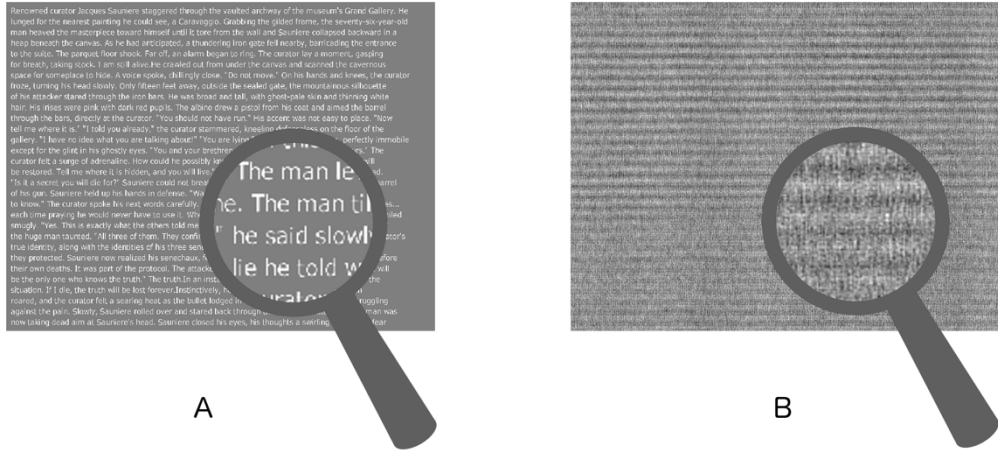
Figure 4.1: A. A sample of the high-contrast text adaptor stimulus, B. the phase scrambled, contrast and luminance matched text adaptor stimulus.

A   B
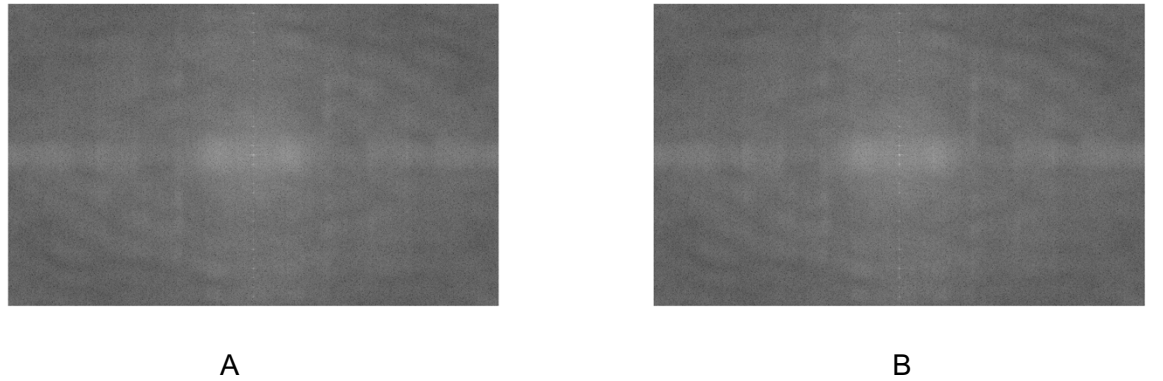
Figure 4.2: A. 2-D amplitude spectrum of original text stimulus, B. 2-D amplitude spectrum of the phase-randomized stimulus.

$$\bar{L} = \frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} L_{ij} \qquad (1)$$

$$C_{mich} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \qquad (2)$$

$$C_{rms} = \frac{1}{MN} \sqrt{\sum_{i=1}^{M} \sum_{j=1}^{N} (L_{ij} - \bar{L})^2} \qquad (3)$$

Contrast sensitivity was measured for 1 cdeg^{-1} and 4 cdeg^{-1} using Gabor test gratings orientated at both 90° (vertical) and 180° (horizontal), and subtended 2.35° visual angle at the screen distance of 52cm.

4.2.4 Procedure

The contrast sensitivity test protocol was the same as that described in section 3.2.4. A QUEST 2AFC procedure was used, wherein participants were requested to push a button to indicate whether a grating appeared to the left or right of a central fixation target. The presentation time for test stimuli was 300ms, using a raised cosine temporal envelope. The termination criterion was set at a confidence level of 95%, and a white circle (size 0.2°) was displayed at the screen centre as a fixation target. The test protocol was explained to participants, who were then given the opportunity to practice until confident with their comprehension of the procedure. Pre-adaptation contrast sensitivity measurements were recorded for Gabor test gratings of 1cdeg^{-1} and 4cdeg^{-1} at both 90° and 180° orientations. One staircase for each stimulus orientation/frequency setting was run, with trials for each of the four test conditions interleaved randomly, terminating at convergence.

The spatial frequencies and orientations measured were the same as that in Experiment 2 to enable comparison of results between the two adaptation conditions (i.e., text vs phase randomised text stimuli). The 1cdeg^{-1} horizontal grating matched the "row frequency," whilst the 4cdeg^{-1} matched the vertical "stroke frequency," of the text adaptor. Orthogonally orientated (1cdeg^{-1} vertical and 4cdeg^{-1} horizontal) Gabors served as corresponding controls for the two frequencies derived from the text stimuli. Three pre-adaptation measurements of contrast sensitivity were obtained at each spatial frequency and orientation, the average of which was taken as the pre-adaptation contrast sensitivity. Following the three pre-adaptation contrast sensitivity measurements, participants were asked to view the phase randomised stimulus for 180s, but since it was incomprehensible, they were not required to read it. After this adaptation period, post-adaptation contrast sensitivity measurement was automatically initiated.

The post-adaptation measurements utilised the top-up procedure described section 3.2.4, such that after every five trials (15s), the phase randomised adaptor stimulus was redisplayed for 30s, after which contrast sensitivity testing recommenced for another 15s followed by 30s stimulus top-up until the staircase was completed for each of the four stimulus conditions. Gabor patches for contrast sensitivity measurement were displayed on the same screen as the adaptor, thereby negating the need for any re-fixation or head movement. An audible beep denoted the commencement of the contrast sensitivity measurement. This seamless alternation between adaptor and contrast sensitivity measurement facilitated rapid, smooth switching between the two tasks, thereby minimising any loss of adaptation that would occur had two different display screens been used.

4.2.5 Analysis

Contrast thresholds were recorded as the common logarithm of the reciprocal of the threshold contrast, i.e. log contrast sensitivity ($\log_{10}CS$). A 2×2×2×2 mixed ANOVA was conducted where $\log_{10}CS$ was the dependent variable. The first within subjects factor was adaptation with two levels (pre-adaptation and post-adaptation). The second within subjects factor was spatial frequency with two levels, (1 and 4cdeg^{-1}). The third within subjects factor was orientation with two levels (horizontal and vertical). The between subjects factor was participant group, with two levels (myopic and emmetropic). A mixed between participants ANOVA was also conducted to compare the results of this experiment with those of Experiment 2.

4.3 Results

The results of the current experiment are first presented independently. Graphs also include the results for Experiment 2 to facilitate comparison: adaptation to text (Experiment 2) is referred to as *condition 1* and adaptation to the phase randomised stimulus is referred to as *condition 2* henceforth.

4.3.1 Pre-adaptation contrast sensitivity

For condition 2, contrast sensitivity measurements were found to be reliable: the COV was calculated for the pre-adaptation $\log_{10}CS$ values for each subject, and for each spatial frequency, to determine the repeatability of the measurements. The standard deviation of each participants' three pre-adaptation $\log_{10}CS$ measurements was divided by the mean of the three $\log_{10}CS$ values to give the COV. When COV is expressed as a percentage it is the relative standard deviation. The mean COV for all participants and spatial frequencies was 4.15% (range: 0-10.45%) and all values were within the acceptable range defined by Lesmes et al. (2010). However, a paired *t*-test did show a statistically significant difference in the mean COV between conditions 1 and 2 ($t_{(79)}$ = -6.47; $p < 0.01$).

Independent samples *t*-tests show no significant difference in pre-adaptation $\log_{10}CS$ between refractive error groups in condition 2: 1cdeg^{-1} vertical $t_{(18)}$ = -0.42; $p = 0.68$ (two-tailed); 1cdeg^{-1} horizontal $t_{(18)}$ = 0.62; $p = 0.54$ (two-tailed); 4cdeg^{-1} vertical $t_{(18)}$ = -1.17; $p = 0.26$ (two-tailed); 4cdeg^{-1} horizontal $t_{(18)}$ = 0.06; $p = 0.95$ (two-tailed).

4.3.2 Post-adaptation contrast sensitivity

There was a significant main effect of spatial frequency [Wilks' Lambda = 0.26; $F_{(1,18)}$ = 50.6, $p < 0.01$, $\eta_p^2 = 0.74$], but no significant main effect of adaptation [Wilks' Lambda = 0.99; $F_{(1,18)}$ = 0.16, $p = 0.70$, $\eta_p^2 = 0.01$], orientation [Wilks' Lambda = 0.97; $F_{(1,18)}$ = 0.15, $p = 0.63$, $\eta_p^2 = 0.03$] or participant group [$F_{(1,18)}$ = 0.03, $p = 0.86$, $\eta_p^2 < 0.01$]. Furthermore, there

was no significant interaction amongst any of the within and between subject factors. Figure 4.3 and Table 4.2 show mean pre- and post-adaptation $\log_{10}CS$ when measured with both horizontal and vertical test gratings at $1cdeg^{-1}$ and $4cdeg^{-1}$ for all participants (left), emmetropic participants (centre) and myopic participants (right).
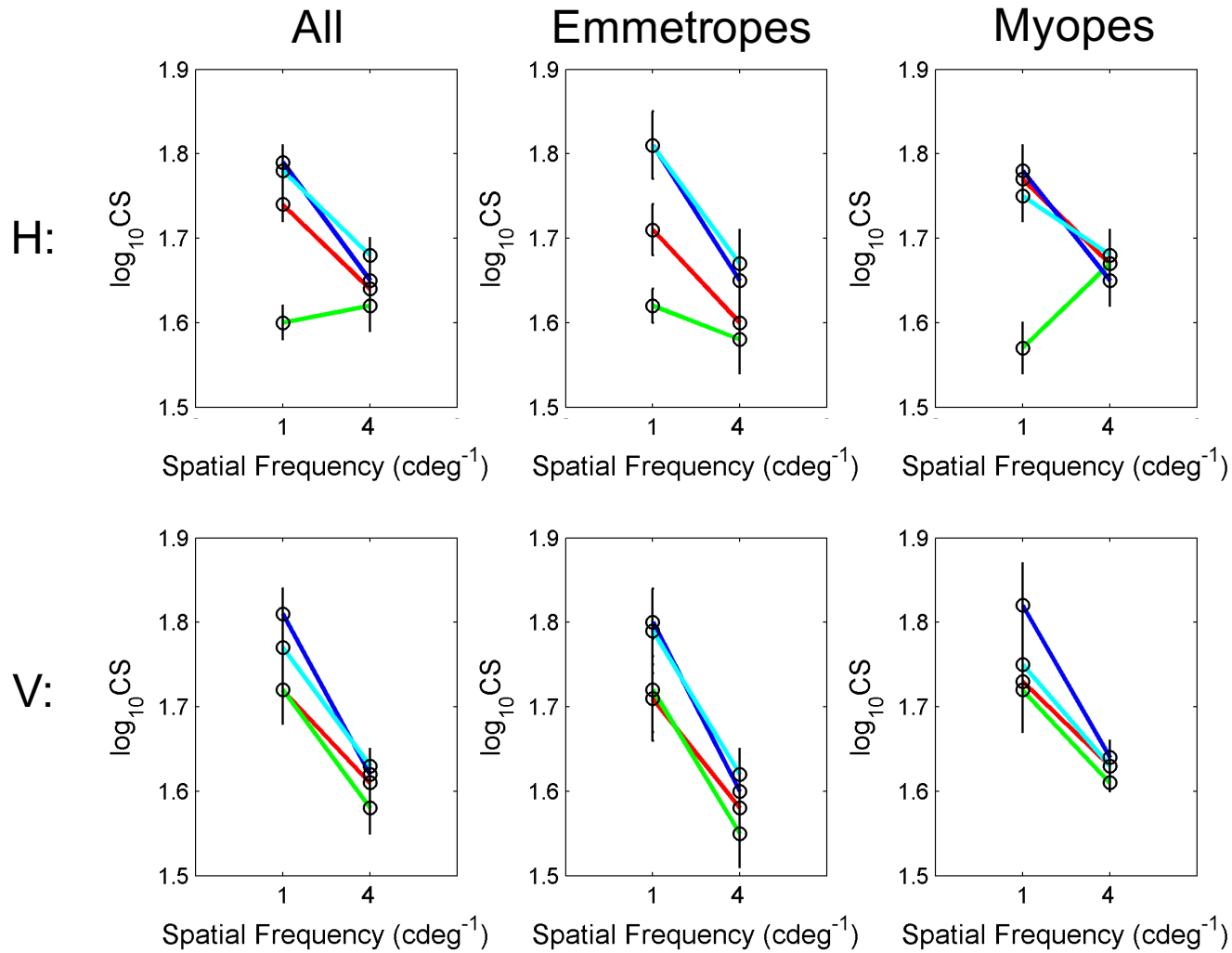
Figure 4.3: Mean pre-adaptation (condition 1: red line; condition 2: blue line) and post-adaptation (condition1: green line; condition 2: cyan line) log$_{10}$CS for horizontal (H: upper row) and vertical (V: lower row) test gratings for all participants (left), emmetropes (centre) and myopes (right). Error bars show ± 1 SEM.

Spatial Frequency	Orientation	Participant Group					
		All		Emmetropic		Myopic	
		Pre	Post	Pre	Post	Pre	Post
1cdeg^{-1}	H	1.79 ± 0.02	1.78 ± 0.03	1.81 ± 0.03	1.81 ± 0.04	1.78 ± 0.03	1.75 ± 0.03
	V	1.81 ± 0.03	1.77 ± 0.03	1.80 ± 0.04	1.79 ± 0.05	1.82 ± 0.05	1.75 ± 0.03
4cdeg^{-1}	H	1.65 ± 0.02	1.68 ± 0.02	1.65 ± 0.04	1.67 ± 0.04	1.65 ± 0.03	1.68 ± 0.03
	V	1.62 ± 0.02	1.63 ± 0.02	1.60 ± 0.03	1.62 ± 0.03	1.64 ± 0.02	1.63 ± 0.02

Table 4.2: Mean $\log_{10}$CS values pre-post adaptation to the phase randomised stimulus ± 1 SEM (log unit) for all participants, emmetropes and myopes for each test grating.

4.3.3 Contrast adaptation

A mixed between-within participants ANOVA was conducted to compare $\log_{10}$CS before and after reading (i.e., adaptation) in myopic and emmetropic participants for each spatial frequency and orientation for condition 2 (Table 4.3). Contrast adaptation was defined as the magnitude of change in $\log_{10}$CS pre-post text adaptation (Figure 4.4 and Table 4.4).

Spatial frequency	Orientation	Wilks' Lambda	$F_{(1,9)}$	p	η_p^2
1cdeg^{-1}	H	0.99	0.15	0.69	0.01
	V	0.95	0.86	0.37	0.05
4cdeg^{-1}	H	0.90	2.12	0.16	0.11
	V	1.00	0.40	0.84	<0.01

Table 4.3: Results of mixed model ANOVA to determine adaptation effects at each spatial frequency and orientation.
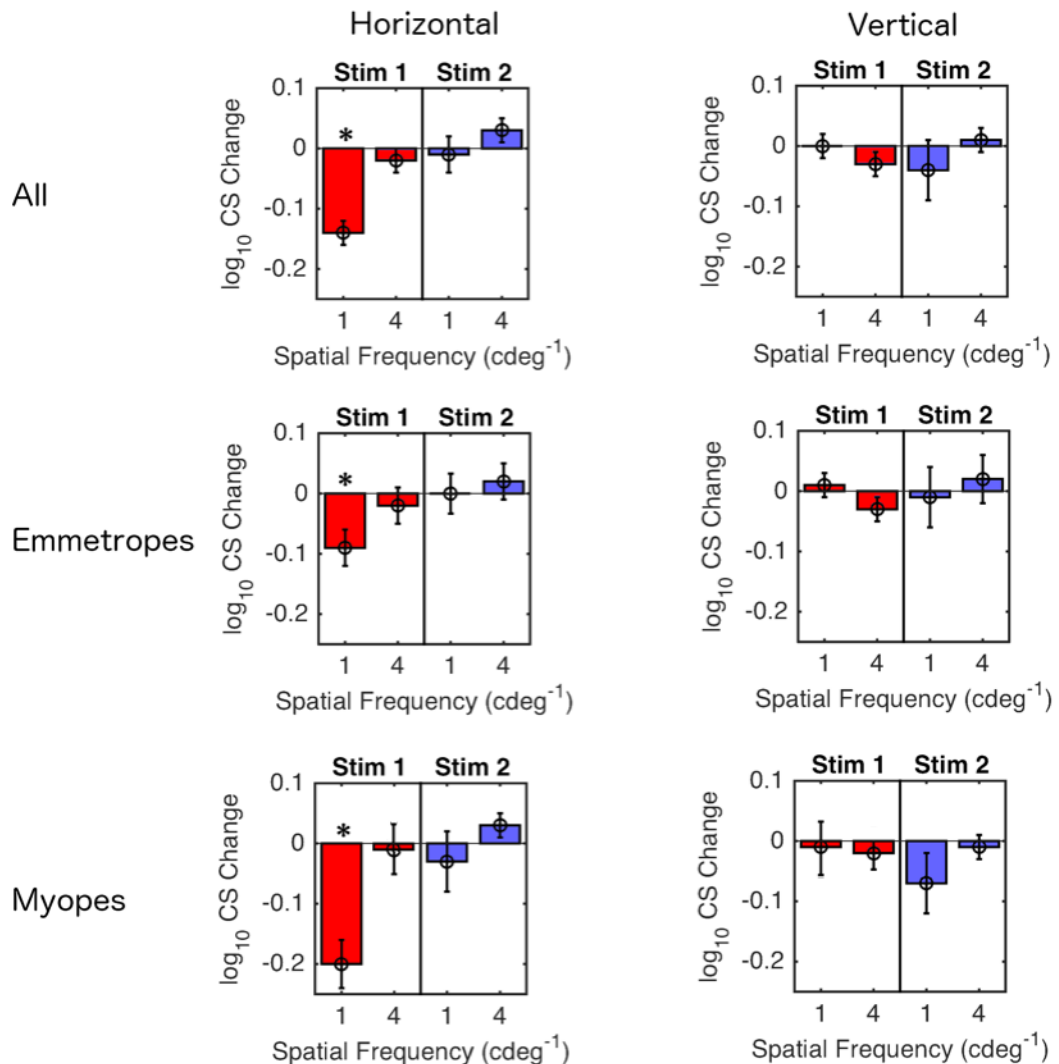
Figure 4.4: $\log_{10}$CS change (contrast adaptation) after text adaptation (stim 1: red bars) and phase randomised stimulus adaptation (stim 2: blue bars) for horizontal (first column) and vertical (second column) test gratings at 1 and 4cdeg^{-1} for all participants (first row), emmetropes (second row) and myopes (third row). Error bars show ± 1 SEM. *denotes contrast adaptation significant at $p \leq .05$.

		Participant Group					
Spatial Frequency	Orientation	All		Emmetropic		Myopic	
1cdeg^{-1}	H	-0.01 ± 0.03		0.00 ± 0.03		-0.03 ± 0.05	
	V	-0.04 ± 0.05		-0.01 ± 0.05		-0.07 ± 0.04	
4cdeg^{-1}	H	0.03 ± 0.02		0.02 ± 0.04		0.03 ± 0.02	
	V	0.01 ± 0.02		0.02 ± 0.04		-0.01 ± 0.02	

Table 4.4: log contrast adaptation ± 1 SEM (log unit) (post-adaptation $\log_{10}$CS – pre-adaptation $\log_{10}$CS) values for all participants, emmetropes and myopes for each test grating. *denotes contrast adaptation significant at $p \leq 0.05$.

		Participant Group					
		All		Emmetropic		Myopic	
Spatial Frequency	Orientation	$t_{(19)}$	p	$t_{(9)}$	p	$t_{(9)}$	p
1cdeg^{-1}	H	0.40	0.69	-0.04	0.96	0.58	0.58
	V	0.94	0.36	0.11	0.91	1.61	0.14
4cdeg^{-1}	H	-1.49	0.15	-0.55	0.59	-2.01	0.08
	V	0.20	0.84	-0.65	0.53	0.48	0.65

Table 4.5: Results of paired t-tests comparing pre- and post-adaptation mean $\log_{10}$CS for each spatial frequency and for all participants, emmetropes and myopes. *denotes significant difference in $\log_{10}$CS pre-post adaptation at $p \leq 0.05$.

Table 4.5 shows the results of paired *t*-tests comparing pre- and post-adaptation $\log_{10}$CS after adaptation to the phase randomised stimulus. There was no significant difference in mean $\log_{10}$CS for any of the spatial frequencies or orientations tested for all participants, myopes or emmetropes. Independent samples *t*-tests compared the magnitude of contrast adaptation between refractive error groups (Table 4.6).

Spatial frequency	Orientation	$t_{(18)}$	*p*
1cdeg^{-1}	H	0.49	0.68
	V	0.80	0.44
4cdeg^{-1}	H	0.00	1.00
	V	0.62	0.54

Table 4.6: Independent samples *t*-tests comparing magnitude of mean contrast adaptation between emmetropic and myopic participants.

A mixed between participants ANOVA was conducted for each spatial frequency and orientation to compare the magnitude of adaptation observed in condition 1 vs. condition 2. (Table 4.7). For 1cdeg^{-1} horizontal, a significant effect of adaptation condition was found [$F_{(1)}$ = 12.45; *p* < 0.01, η_p^2 = 0.26], along with a significant effect of refractive error group [$F_{(1)}$ = 3.63; *p* = 0.05, η_p^2 = 0.10]. However, the interaction between these two factors was not found to be significant [$F_{(1)}$ = 1.40; *p* = 0.24, η_p^2 = 0.04]. There was no significant effect of refractive error group, adaptation condition or interaction between the two for the other three tested spatial frequencies and orientations (table 4.7).

Spatial frequency	Orientation	Condition			Rx Group			Condition * Rx Group		
		$F_{(1, 38)}$	p	η_p^2	$F_{(1, 38)}$	p	η_p^2	$F_{(1, 38)}$	p	η_p^2
1cdeg^{-1}	H	12.45	< 0.01*	0.26	3.63	0.05*	0.10	1.40	0.24	0.04
	V	0.52	0.48	0.01	1.53	0.22	0.41	0.02	0.87	<0.01
4cdeg^{-1}	H	2.45	0.13	0.06	0.08	0.78	<0.01	0.08	0.78	<0.01
	V	2.04	0.16	0.05	0.06	0.81	<0.01	0.57	0.46	0.02

Table 4.7: Results of mixed between participants ANOVA comparing the amount of contrast adaptation for each spatial frequency and orientation in each adaptation condition and between refractive error groups. *denotes significant effect at $p \leq 0.05$.

4.4 Discussion

4.4.1 Adaptation to a phase randomised stimulus

Participants in this study adapted to a stimulus with identical spatial frequency, orientation, contrast and luminance properties to the text stimulus used in Experiment 2. The stimulus differed in that phase information was randomised, which rendered it incomprehensible, despite retaining the superficial appearance of text. No significant change in contrast sensitivity and no adaptation effects were observed for the two spatial frequencies derived from the text row and stroke frequencies in Experiment 2 ($1cdeg^{-1}$ horizontal and $4cdeg^{-1}$ vertical respectively) in either the myopic or emmetropic participant group.

The study was designed to examine the mechanisms that underpin contrast adaptation in reading; in particular, the role of cognition *vs.* the fundamental statistical properties of the adaptor. To address this question, the results of adaptation to the two stimulus classes (used in Experiment 2 and the present Experiment, 3) were compared, which are referred to as condition 1 and condition 2.

4.4.2 Comparing adaptation to text and the phase randomised stimulus

The results of condition 1 are reported in full in Chapter 3, in which contrast adaptation was observed after reading a popular novel at the text row frequency ($1cdeg^{-1}$ horizontal), but not the letter stroke frequency ($4cdeg^{-1}$), and only at orientations that matched the visual properties of the text stimulus (i.e., not at orthogonal control orientations). In the previous study, it was postulated that the absence of adaptation at the letter stroke frequency may be due to insufficient power, or insufficiently narrow-band power at the letter stroke frequency as revealed by a Fast Fourier Transform (FFT) of the stimulus.

A finding of contrast adaptation after reading, as was shown in condition 1, is consistent with extant literature (Lunn & Banks, 1986; Magnussen et al., 1992; Greenhouse et al., 1992; Yeo et al., 2012). Since significant contrast adaptation was not observed using the phase randomised stimulus (condition 2), it is reasonable to surmise that adaptation is principally observed where a readable stimulus (requiring comprehension) serves as an adaptor. Two hypotheses are postulated to account for this observation: (1) that the cognitive effort required to actively read, rather than passively view, a stimulus is needed to educe adaptation; (2) that phase information may be necessary for adaptation to a text stimulus to occur.

This is in stark contrast to simple (e.g. sinusoidal) signals, wherein phase manipulation would produce only a spatial shift in the signal position (Figure 1.4) but would not alter its appearance otherwise. Since frequency, orientation, contrast and luminance were matched between adaptor stimuli in condition 1 and 2, it holds that these features alone are

insufficient to produce significant adaptation, unless accompanied by a corresponding phase channel, despite that these more primitive visual features being the focus of most extant studies of adaptation effects.

This draws into question studies that use simple, sinusoidal stimuli to make deductions about adaptation to text (i.e., generalisations from sinusoids to text), since this experiment demonstrates that adaptation effects depend upon phase for complex stimuli, or upon the act of reading, which limits the degree to which we can generalise findings obtained using simple stimuli. In their study of near vision target type on contrast adaptation, Yeo et al. (2013) found that English and Chinese texts induced similar adaptive effects, but grating adaptation induced a larger effect. By definition a sine wave is *infinitely* narrow whilst any naturally occurring image (including text) is actually infinitely broad: technically, having a spectrum defined by a set of real numbers in the half-closed half-infinite interval $[0,+\infty)$. Some authors may define broad as a relative term, comprising a set of number from some non-infinite interval, and narrow band some interval which is simply smaller.

Blur adaptation studies have shown strong effects when using letter targets, and weaker effects with grating targets. The procedures adopted used blur achieved by removal of myopic refractive correction (Pesudovs & Brennan, 1993; Rosenfield et al. 2004), or fixed levels of positive lens-induced defocus over the best correction (Mon-Williams et al., 1998; George & Rosenfield, 2004) to measure visual acuity under defocus before and after a period of adaptation. Khan, Dawson, Mankowska, Cufflin and Mallen (2013) have shown that blur adaptation effects are achieved rapidly (within 4 to 6 minutes), and in a predictable way with letter targets. In studies examining the effect of blur on visual acuity, a common pattern of greater reductions when using letter targets compared to gratings is seen (Thorn & Schwartz, 1990). Furthermore, when considering blur adaptation effects, the different perceptual tasks of identifying a letter target versus locating the gap in a Landolt C target have influence over the degree of adaptation detected experimentally (Poulere, Moschandreas, Kontadakis, Pallikaris & Plainis, 2013). These findings point towards a different perceptual mechanism for adaptive effects within the visual system to defocus, depending on the cognitive processing required for interpretation of the stimulus.

Investigating blur sensitivity after blur adaptation has yielded conflicting results: Cufflin, Mankowska and Mallen, (2007) found reduced sensitivity whilst Wang, Ciuffreda and Vasudevan, (2006) found increased blur sensitivity after blur adaptation. Comparing refractive error groups, Rosenfield and Abraham-Cohen (1999) used cycloplegia in adult subjects to measure subjective perception of blur and found that myopes were less sensitive to blur than emmetropes. Conversely, Schmid, Iskander, Li, Edwards and Lew (2002) found no correlation between blur thresholds and refractive error magnitude in children, although

they did find that blur detection ability was more variable in myopic children. Target characteristics including size and spatial frequency may also have bearing on detectability which might account for differences found in either of these studies. Brief exposure to image blur has been shown to improve visual acuity (Pesudovs & Brennan, 1993; Mon-Williams et al., 1998; George & Rosenfield, 2004). It is unknown as to whether the blur deficits in myopes are a cause or consequence of myopia.

Vera-Diaz, Gwiazda, Thorn and Held (2004) showed increased near accommodation responses in myopes, but not emmetropes, after three minutes of blur exposure. Adaptation to natural scenes viewed through defocus blur has been shown to increase supra-threshold contrast sensitivity at 3.22cdeg^{-1} (Ohlendorf & Schaeffel, 2009), between 3-4cdeg^{-1} (Venkataraman, Winter, Unsbo & Lundström, 2015) and at 8cdeg^{-1} and 12cdeg^{-1} (Rajeev & Metha, 2010). However, extant studies that have investigated the effect of blur adaptation on contrast sensitivity have not examined the influence of different refractive groups. It is worth highlighting that refractive error was unchanged in all these studies and this is strongly indicative of a perceptual basis to the adaptation.

Conclusion
Together, the results of condition 1 and 2 suggest that adaptation to veridical text is a consequence of the cognitive effort or attention elicited by active reading, or the combined phase, spatial frequency and orientation properties of the stimulus, rather than the spatial frequency and orientation composition of this stimulus class only. However, without further investigation, it is not possible to deduce either the role of cognition or the fundamental statistical properties of the adaptor in eliciting contrast adaptation during reading.

Chapter 5

Experiment 4: Accommodation accuracy before and after reading text and adaptation to a phase randomised stimulus.

5.1 Introduction

A correlation between myopia and education (as discussed in section 1.3.2) has led to speculation that near work is a risk factor for myopia development (see Zadnik, 2007, for review). In particular, a specific association between myopia development and reading has been proposed (Saw et al., 2002; Ip et al., 2008; Huang et al., 2015). The accommodation response initiated during reading is thought to mediate this relationship (section 1.9): an inaccurate accommodation response could result from poor blur perception or it may result from an inadequate neural accommodative response. There may therefore be features in text detail that engender poor blur perception or an inaccurate neural accommodative response in myopic observers. As discussed in section 1.6.2, defocus retinal blur has been shown to be the primary stimulus which initiates an accommodation response.

Myopes have been shown to have higher blur tolerance than emmetropes (Jiang, 1997, Rosenfield & Abraham-Cohen, 1999; George & Rosenfield, 2004) although Schmid et al. (2002) found no correlation between blur thresholds and refractive error magnitude in children. Adaptation to defocus blur has been shown to influence the subjective sensitivity to blur (Rosenfield & Abraham-Cohen, 1999; Schmid et al., 2002; Wang et al., 2006; Cufflin et al., 2007) and to the accommodation response (Vera-Diaz et al, 2004) in both emmetropes and myopes. These studies compared blur sensitivity, and static and dynamic accommodative responses pre-post blur adaptation; however, accommodative responses have not been investigated after a period of adaptation for *in-focus* text targets. Whilst imposed defocus may simulate the visual experience of an uncorrected myope, this does not explain the role of near work as a myopigenic stimulus prior to myopia onset, or when the myope is corrected with spectacle or contact lenses. Therefore, investigating adaptation to in-focus text targets (as corrected myopes would perceive them), rather than targets viewed through optical defocus, may be more informative in understanding the role of near work in myopia development.

Myopes have been shown to have higher accommodative lag (McBrien & Millodot, 1986; Gwiazda et al., 1993b; Gwiazda et al., 2005; Nakatsuka et al., 2005; Yeo et al., 2006). This, coupled with their reduced sensitivity to blur could result in even larger accommodative lags as they tolerate a larger magnitude of retinal blur before an accommodative response is initiated. The hypermetropic defocus which results from a lag of accommodation is thought to trigger the growth process that produces compensatory myopia (Goss & Wickham 1995).

Previous studies comparing accommodative lag in different refractive error groups have shown young progressing myopes to have larger lags than emmetropes (Gwiazda et al., 1993b; Gwiazda et al., 1995a; He, Gwiazda, Thorn, Held & Vera-Diaz, 2005; Nakatsuka et al., 2005; Allen & O'Leary, 2006). However, in adults with stable myopia, the mean lag has been found to be closely comparable to emmetropes (Abbott et al., 1998; Nakatsuka et al., 2003; Seidemann & Schaeffel, 2003; Allen & O'Leary, 2006; Harb et al., 2006).

Accommodative lag has been shown to increase with closer reading distance (Charman, 1999; Gwiazda et al., 1993b; Seidemann & Schaeffel, 2003; Harb et al., 2006). In addition, viewing and measurement were conducted monocularly for the majority of these experiments, with targets placed in a Badal system. This would have limited the normal detection cues available, which may disadvantage participants who use other cues (e.g., proximal or directional) more effectively than blur. Studies have reported that children accommodate less accurately to minus-lens induced blur (Gwiazda et al., 1993b; Chen and O'Leary, 2000; Anderson et al., 2009) and Badal targets (Mutti et al., 2006) compared to real targets.

Chapter 3 describes significant contrast adaptation for the row frequency of veridical text after reading (which was significantly greater for myopic participants), whilst adaptation to an incomprehensible phase randomised stimulus in Chapter 4 revealed no significant contrast adaptation in either refractive error group. It was hypothesised that this was either a consequence of the cognitive effort elicited by active reading, or that the phase properties of the text stimulus were necessary. Several earlier studies have demonstrated that variation in cognitive effort produces significant changes in the accommodative response (Kruger 1980; Malmstrom et al., 1980; Winn et al., 1981; Malmostrom & Randle, 1984; Birnbaum, 1984; Bullimore and Gilmartin 1988; Rosenfield & Ciuffreda, 1990; Rosenfield & Ciuffreda, 1994). Myopes showed a significantly greater positive shift in tonic accommodation than emmetropes (Bullimore & Gilmartin, 1987) after a cognitive counting task, and Wolffsohn et al. (2003) showed that the level of cognitive activity determined the persistence of NITM in myopes but not emmetropes. Such refractive group differences suggest that there may be an influence from non-optical factors, such as cognitive effort in the initiation of an optimal accommodation response, which, if degraded, may be myopigenic. Greater attention to a task may require more accurate accommodation (Bullimore & Gilmartin, 1988). Bernsten et al. (2011) suggesting that tasks with greater cognitive demand would be expected to slightly reduce the degree of accommodative lag measured.

Accommodative accuracy has previously been compared after adaptation to a computer game (Jiang & White, 1999), where a larger accommodative lag was shown post

adaptation. Moreover, there was no significant difference between emmetropes and late-onset myopes. In their study, the accommodative demand was 6.00D (the target was viewed through a -4.00D lens at 50cm). This is equivalent to a 16cm viewing distance, which is atypical for most peoples' near work.

In the present study, the monocular accommodative response of young emmetropic and myopic adults was measured pre- and post- binocular adaptation to the same text stimulus from Chapter 3 (*condition 1*) and the phase randomised stimulus from Chapter 4 (*condition 2*). This study was undertaken to ascertain whether reading altered the accuracy of the accommodative response differently in the two refractive error groups, whilst simultaneously investigating whether the cognitive effort required to read has any bearing on the accommodative response, and thus the magnitude of hypemetropic blur that might act as a stimulus to axial elongation. The hypothesis was that myopic participants would show a greater accommodative lag than emmetropic participants after reading text (condition 1), concurrent with reduced contrast sensitivity in Chapter 3. The second hypothesis was that accommodative lag would be lower post-adaptation in condition 1 than condition 2, following the suggestion, by Bernsten et al. (2011), that greater cognitive effort (as required for reading comprehensible text in condition 1) would reduce accommodative lag. This would imply a preference for the role of cognitive demand rather than stimulus phase in inducing contrast adaptation in experiment 2, and could help expand the understanding of the association between increasingly competitive and rigorous education systems (involving prolonged reading) and increasing myopia prevalence (see Morgan, Ohno-Matsui & Saw, 2012 for a review).

5.2 Method

5.2.1 Participants

A power analysis indicated that for a difference in accommodative response after adaptation, based on Cufflin et al. (2007) and an $\alpha = 0.05$, 20 subjects (10 myopes and 10 emmetropes) would be required to give a statistically significant difference between groups with a power of 90%.

All participants were recruited from the student population at Anglia Ruskin University. Two participant cohorts completed each condition: participants in condition 1 were the same as those who took part in experiment 2 (Chapter 3) whilst participants in condition 2 were the same as those in experiment 3 (Chapter 4). Six emmetropic and five myopic participants completed both conditions (visits were separated by at least three months).

Twenty young adults took part in each condition, ten of whom were classified as myopic (spherical equivalent refraction, sphere + ½ cylinder [SER]) (SER > -0.75D) and 10 emmetropic (SER +0.50 to -0.25D). The participants in each group are summarised in Table

5.1. Refractive error was determined by subjective assessment of maximum plus consistent with best visual acuity to the nearest 0.25D.

Condition	Measure	Participant Group	
		Emmetropic	Myopic
1 (veridical text)	Mean age (y) ± SD	21.44 ± 3.09	25.89 ± 4.26
	Gender (male:female)	4:6	5:5
	Mean SER ± SD (D)	0.01 ± 0.14	-2.94 ± 1.69
2 (phase randomised stimulus)	Mean age (y) ± SD	23.7 ± 5.19	25.0 ± 4.03
	Gender (male:female)	7:3	4:6
	Mean SER ± SD (D)	0.01 ± 0.14	-2.78 ± 1.40

Table 5.1: mean age, gender and mean spherical equivalent refractive error (SER) for emmetropic and myopic participant groups for condition 1 and 2.

Inclusion criteria were: best-corrected acuity ≤ 0.00 logMAR in each eye; monocular Pelli-Robson Chart log contrast sensitivity ≥ 1.65; SER between -5.00DS and +0.50DS; astigmatism ≤0.75DC, anisometropia ≤ 1.00D, an absence of ocular pathology and suitability for contact lens wear. All participants were fully corrected for their spherical equivalent distance correction with Biotrue ONEday soft contact lenses (Bausch & Lomb, fitting parameters: base curve 8.6mm; total diameter 14.2mm; Dk/t 42 @ centre for -3.00 and water content 78%). All tasks were performed binocularly.

Informed written consent (Appendix B) was obtained from all participants following an explanation of the experiment. Procedures were approved by the University ethics panel, and followed the tenets of the Declaration of Helsinki.

5.2.2 Apparatus

Accommodative lag was measured as participants viewed the near stimulus presented on a 19'' Sony Trinitron GDM-F520 CRT at 0.52m (section 3.2.2). In condition 1, this was English text (see section 3.2.3) and in condition 2, participants observed the phase randomised stimulus described in section 4.2.3.

Auto-refraction is the gold standard for measurement of accommodative lag (Manny et al., 2009), and measurements were obtained with the use of the Shin Nippon SRW-5000 auto-refractor. Used in an unaltered static mode, it objectively measures the refractive state of the eye. Refractive error is calculated in two steps by means of an infrared open view autorefractor, as described by Mallen, Wolffsohn, Gilmartin & Tsujimura, (2001). A ring image from an infrared source (850nm) is reflected from the retina and analysed across a pupil diameter of 3mm. The image is then digitally analysed in multiple meridians to calculate a toroidal prescription. The range of measureable refractions is ±22D sphere and ±10D cylinders in 0.125D steps and cylinder axis to 1°. It has been reported to have good

accuracy when compared to subjective refraction and good repeatability in both children (Chat & Edwards, 2001) and adults (Mallen et al., 2001). The device provides a relatively wide, open field-of-view of test stimuli.

5.2.3 Procedure

The experimental setup for measuring accommodative lag is shown in Figure 5.1. Participants first spent 5min in darkness to open the accommodation loop and dissipate the effects of any previous near activity (Ciuffreda & Wallis, 1998; Chen et al., 2003; Schmid et al., 2005). Participants were seated at the edge of an optical bench and positioned at the chin and brow rest of the autorefractor through which they could see the adaptor stimuli at 0.52m (accommodative demand 1.92D). The auto-refractor was aligned to take measurements from the right eye. Pre-adaptation, they were asked to fixate the adaptor stimulus and keep it as clear as possible whilst 5 auto-refractor readings were taken of the right eye.
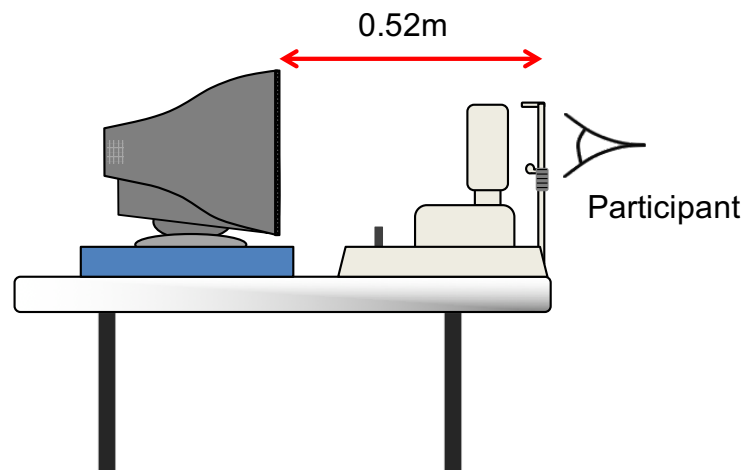
Figure 5.1: Experimental setup for the measurement of accommodative lag.

In condition 1, participants were instructed to read silently and as they would normally for 3 min. They were not tested for reading speed or comprehension of the text. After 3 min reading, 5 post-adaptation auto-refractor readings were obtained from the right eye. In condition 2, the procedure was identical to condition 1, except that the phase randomised adaptor stimulus was used and subjects were asked to just scan the stimulus as it was otherwise incomprehensible. Attempts were made to limit the influence of optical factors by keeping the visual nature of the task and the angular subtense of the stimuli the same for both adaptation conditions.

A 3 min reading time was selected to replicate the 3 min reading duration in Chapter 3 and 4. Vera-Diaz et al. (2004) also measured accommodative responses after 3 min blur adaptation who followed the adaptation paradigm of Webster, Georgeson and Webster, (2002). Harb et al. (2006) found accommodative errors were greatest during the first 3 min

of reading and then remained stable throughout the remainder of the reading period. A reduction in the lag of accommodation during the first few minutes of reading has previously been observed and may be due to an increased output of a slow, blur-driven, accommodative response mediated by the sympathetic nervous system (Rosenfield & Gilmartin, 1998, Schor, Kotulak & Tsuetaki, 1986).

5.2.4 Analysis

Auto-refractor readings were converted to equivalent best sphere values by adding half the cylinder value to the spherical component and then the mean of 5 readings was determined. Invalid auto-refractor readings (resulting from blinking or fixation loss) that gave large cylindrical components > -1.00DC were excluded. The sign of the spherical equivalent was changed (plus to minus or minus to plus) and this value subtracted from the demand of 1.92D at near to give accommodative lag if positive or lead if negative.

A 2×2 mixed ANOVA was run with accommodative lag as the dependent variable. The within subjects factor was adaptation, with two levels (pre-adaptation and post-adaptation. The between subjects factor was participant group. Separate analyses were completed for conditions 1 and 2. An additional two-way ANOVA was conducted where the between participants factor was changed to adaptation condition.

5.3 Results

5.3.1 Condition 1: Text adaptation

Table 5.2 and Figure 5.2 show mean accommodative lag pre-adaptation and post-text adaptation for all participants, emmetropic participants and myopic participants. A mixed between-within participants ANOVA was conducted to compare accommodative lag before and after reading (i.e., adaptation) in myopic and emmetropic participants. There was a significant adaptation effect [Wilks' Lambda = 0.71; $F_{(1,18)}$ = 7.43, p = 0.01, η_p^2 = 0.29] with both refractive error groups showing increased accommodative lag after reading.

	Participant group		
Condition	**All**	**Emmetropic**	**Myopic**
Pre-adaptation	0.50 ± 0.06	0.44 ±0.09	0.57 ± 0.06
Post-adaptation	0.68 ± 0.07	0.53 ± 0.08	0.84 ± 0.10

Table 5.2: Accommodative lag (D) pre-adaptation and post-text adaptation for all participants, emmetropic and myopic participants (mean ± 1 SE).
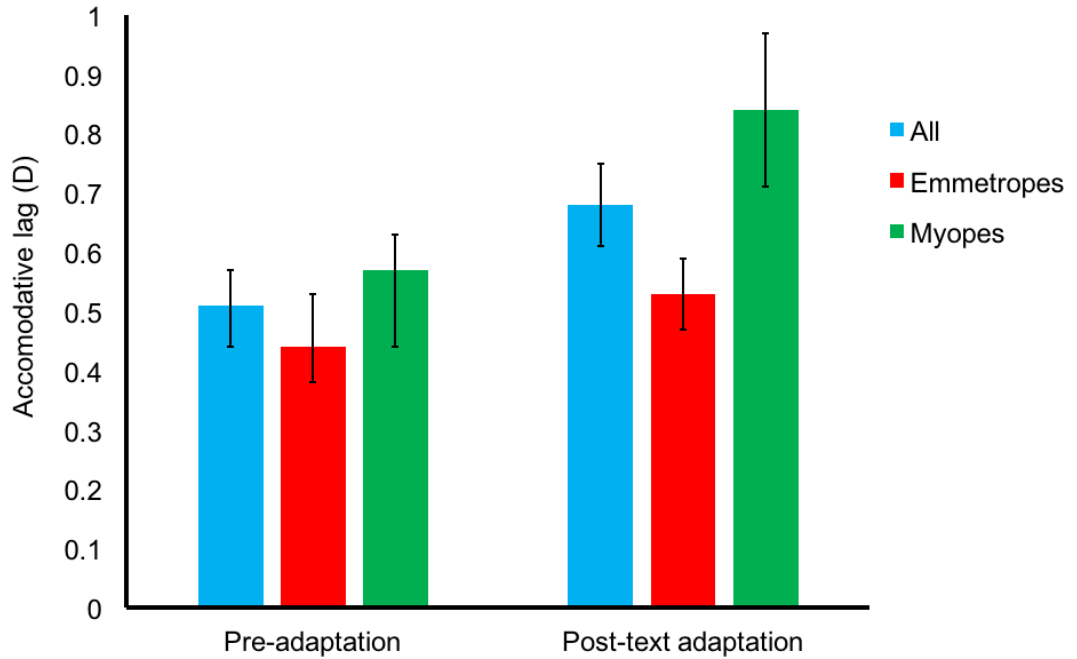
Figure 5.2: Accommodative lag (D) pre-adaptation and post-text adaptation for all participants, emmetropic and myopic participants (error bars show mean ± 1 SE).

Pre-adaptation accommodative lag was not significantly different between emmetropic and myopic participants; independent samples *t*-test [$t_{(18)}$ = -1.13; *p* = 0.27 (two-tailed)]. Post-adaptation, myopic participants had marginally significantly greater accommodative lags than emmetropes [$t_{(18)}$ = -2.31; *p* = 0.03 (two-tailed)].

Comparing accommodative accuracy pre-post adaptation, both refractive error groups showed an increase in accommodative lag after reading text which was marginally significant for myopic participants [$t_{(9)}$ = -2.26; *p* = 0.04 (two-tailed)] but not for emmetropic participants [$t_{(9)}$ = -0.92; *p* = 0.38 (two-tailed)].

However, the magnitude of change in accommodative lag was not significantly different between the two refractive error groups [independent samples *t*-test: $t_{(18)}$ = -1.36; *p* = 0.19 (two-tailed)].

5.3.2 Condition 2: Phase randomised stimulus adaptation

Table 5.3 and Figure 5.3 show mean accommodative lag pre-adaptation and post-phase randomised stimulus adaptation for all participants, emmetropic participants and myopic participants. A mixed between within participants ANOVA was conducted to compare accommodative lag before and after adaptation to the phase randomised stimulus in myopic and emmetropic participants. There was no significant adaptation effect [Wilks' Lambda = 0.93; $F_{(1,18)}$ = 0.42, *p* = 0.25, η_p^2 = 0.07]

	Participant group		
Condition	All	Emmetropic	Myopic
Pre-adaptation	0.61 ± 0.05	0.54 ±0.05	0.68 ± 0.09
Post-adaptation	0.70 ± 0.07	0.67 ± 0.06	0.72 ± 0.13

Table 5.3: Accommodative lag (D) pre-adaptation and post-phase randomized text adaptation for all participants, emmetropic and myopic participants (mean ± 1 SEM).
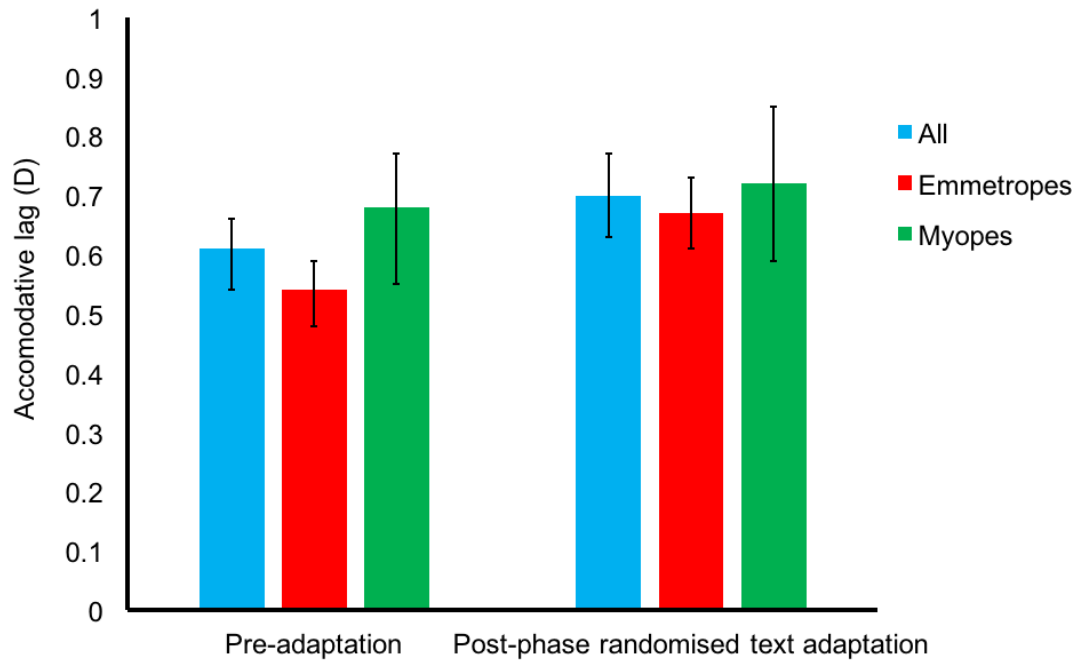
Figure 5.3: Accommodative lag (D) pre-adaptation and post-phase randomized text adaptation for all participants, emmetropic and myopic participants (error bars show mean ± 1 SE).

Pre-adaptation accommodative lag was not significantly different between emmetropic and myopic participants; independent samples *t*-test [$t_{(18)}$ = -1.38; *p* = 0.18 (two-tailed)]. Although mean accommodative lag was greater after adaptation to the phase randomised stimulus, paired *t*-tests showed that the change was not significant in all participants [$t_{(19)}$ = -1.22; *p* = 0.24 (two-tailed)], in emmetropic participants [$t_{(9)}$ = -1.46; *p* = 0.17 (two-tailed)] and myopic participants [$t_{(9)}$ = -0.36; *p* = 0.73 (two-tailed)]. The change in accommodative accuracy was not significantly different between the two refractive error groups [independent samples *t*-test: $t_{(18)}$ = 0.64; *p* = 0.53 (two-tailed)]. Furthermore, there was no significant difference between the post-adaptation accommodative lag between the refractive error groups [independent samples *t*-test: $t_{(18)}$ = -0.35; *p* = 0.73 (two-tailed)].

5.3.3 Comparing condition 1 and 2

Pre-adaptation accommodative lag was compared for conditions 1 and 2 as not all participants took part in both conditions. Independent samples *t*-test showed no significant difference in participants' pre-adaptation accommodative lag in conditions 1 and 2 (independent samples *t*-test [$t_{(38)}$ = -1.09; *p* = 0.28 (two-tailed)].

A mixed between participants ANOVA was conducted to compare the amount of change in lag pre-post adaptation between conditions 1 and 2. There was no significant effect of adaptation condition [$F_{(1,38)}$ = 0.99; p = 0.33, η_p^2 = 0.03] or refractive error group [$F_{(1)}$ = 0.23; p = 0.65, η_p^2 = 0.01] nor was the interaction between the two significant [$F_{(1)}$ = 1.96; p = 0.17, η_p^2 = 0.05].

Table 5.4 and Figure 5.4 show mean values for the amount of change in accommodative lag pre-post adaptation in each condition for all participants, emmetropes and myopes.

Condition	Participant Group		
	All	**Emmetropic**	**Myopic**
Condition 1	0.18 ± 0.07	0.09 ±0.09	0.27 ± 0.09
Condition 2	0.08 ± 0.06	0.13 ± 0.08	0.04 ± 0.09

Table 5.4: Mean change in accommodative lag pre-post adaptation for condition 1 and 2, for all participants, emmetropes and myopes (mean ± 1 SE).
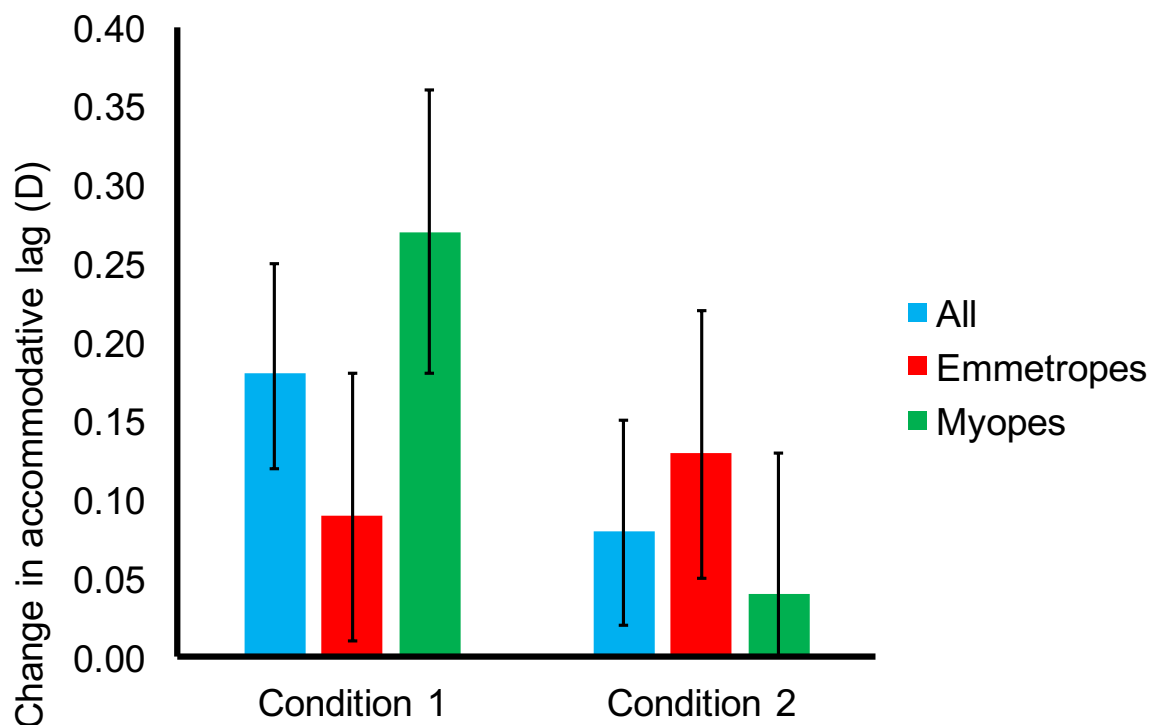
Figure 5.4: Change in accommodative lag (D) pre-post adaptation for conditions 1 and 2. (error bars show mean ± 1 SE).

The difference in the change in accommodative lag pre-post adaptation between condition 1 and 2 was not significant [independent samples t-test: $t_{(38)}$ = 0.80; p = 0.43 (two-tailed)]. When split by refractive error group, the change was not significant for either emmetropes [independent samples t-test: $t_{(18)}$ = -0.31; p = 0.76 (two-tailed)] or myopes [independent samples t-test: $t_{(18)}$ = 1.35; p = 0.19 (two-tailed)].

5.4 Discussion

5.4.1 Condition 1

Mean accommodative lag after reading text (mean ± SE; 0.68 ± 0.07D) was comparable to that reported for young adults during reading by Harb et al. (2006) (0.69 ± 0.08D). Young progressing myopes have been shown to have larger lags than emmetropes (Gwiazda et al., 1993b; Gwiazda et al., 1995a, He et al., 2005; Nakatsuka et al., 2003; Allen & O'Leary, 2006), whilst in adults with stable myopia, mean lag is the same as emmetropes (Abbott et al., 1998; Nakatsuka et al., 2003; Allen & O'Leary, 2006; Seidemann & Schaeffel, 2003; Harb et al., 2006). The participants in the current study were also young adults, but their age of myopia onset and stability of refractive error was not specified. However, the finding that pre-adaptation lag was equal in emmetropic and myopic participants is consistent with these earlier studies.

After reading the text stimulus for three minutes, accommodative lag increased significantly in myopic participants but not emmetropic participants, and therefore the null hypothesis is rejected. These were the same myopic participants who displayed significantly greater accommodative lag after reading in myopic participants contradicts the finding of Vera-Diaz et al. (2004) who found that whilst young adult myopes showed a significant increase in the near accommodative response after three minutes of blur adaptation, emmetropes did not.

Bullimore and Gilmartin (1988) suggest that greater attention to a task may require more accurate accommodation. However, the results of the present experiment indicate that reading text may result in myopes being less able to make an accurate accommodation response when compared with emmetropes.

5.4.2 Condition 2

The results of this study also show that in condition 2, mean pre-adaptation accommodative lag was comparable in emmetropic and myopic participants. Accommodative accuracy was not significantly different after three minutes adaptation to the phase randomised stimulus, or between refractive error groups post-adaptation in condition 2. This was the same participant cohort who did not show contrast adaptation after adaptation to the phase randomised stimulus in Experiment 3 (Chapter 4).

5.4.3 Comparing condition 1 and 2

There was no significant difference in pre-adaptation lag between participants in condition 1 and 2, allowing these paradigms to be compared using the two slightly different participant groups. Berntsen et al. (2011) suggested that greater cognitive effort would reduce accommodative lag, hence the hypothesis stated in section 5.1, that one would expect post-

adaptation accommodative lag to be lower for condition 1 than condition 2. However, in this study, mean accommodative lag increased in both conditions post-adaptation. Furthermore, the mean change in accommodative lag was greater for condition 1, for which the cognitive demand was greater. Despite showing greater mean accommodative lag after reading text (mean ± SE; 0.18 ± 0.07D) compared to adaptation to the phase randomised stimulus (0.08 ± 0.06D), the difference in the magnitude of change between the two adaptation conditions was not significant, most likely due to the large standard error values (i.e., measurement dispersion). Comparing refractive error groups, emmetropic participants showed a greater increase in lag after adaptation to the phase randomised stimulus than after reading text, whilst the opposite was true for myopes, but again relatively large dispersion may have rendered any small effect non-significant. It will be necessary, in future work, to increase the participant cohort size to more reliably establish any influence of cognitive demand on accommodation response.

5.4.4 General discussion

Studies have suggested increases in accommodative lag occur before myopia onset (Goss, 1991; Drobe & Saint-André, 1995; Gwiazda et al., 2005), but it has also been suggested that increased accommodative lag is a consequence of myopia development (Mutti et al., 2006). The current study was cross-sectional, and thus whether or not the increased accommodative lag shown in myopic participants after text adaptation is a cause or consequence of their myopia cannot be conclusively determined. However, coupled with the finding of a greater change in contrast sensitivity after reading in myopes, these results do imply that they are more susceptible to the effects of adaptation.

Animal studies show changes in eye growth after two to three minutes of optical defocus (Zhu et al., 2005; Zhu & Wallman, 2009). The greater contrast adaptation and increased accommodative lag after reading in myopes shown after only three minutes in this thesis could be even more detrimental if the reading task duration were increased or uninterrupted with distant viewing as would be typical in an academic context. The small amounts of defocus experienced during reading could be sufficient to produce a change myopigenic change in axial length.

Bour (1980) described phase as not being important for dynamic accommodation responses or microfluctuations and Hess, Schmid, Dumoluin, Field and Brinworth (2006) found that the spatial frequency content and not the stimulus phase was important for the development of deprivation myopia in chicks. A significant reduction in accommodative accuracy in myopes after reading text but not after viewing the phase randomised stimulus supports the hypothesis that it is cognitive effort that influences the contrast adaptation measured in Experiment 3. Additionally, cognitive effort has only previously been

investigated with numeracy tasks. The literacy task as used in this experiment suggests that it is reasonable to propose that this is more informative in ascertaining the the role of reading in inducing contrast adaptation as a proxy for myopia progression.

Fast Fourier Transform (FFT) of the text adaptor in condition 1 (section 3.4, Figure 3.6) revealed insufficient power/insufficient narrow-band power at the letter stroke frequency (4cdeg^{-1}). As mid range spatial frequencies have been identified as being responsible for eliciting optimal accommodative responses (Ward, 1987; Bour, 1981; Owens, 1980), it is reasonable to assume that had there been greater power at 4cdeg^{-1}, then it is plausible that accommodation may have been even more adversely affected than shown here.

In this study, increased accommodative lag was found in myopic participants following adaptation to text on a screen, but of course text is often read as hard copy print too. Freivalds, Harpster and Moussaoui (1989) demonstrated that accommodation was more accurate with hard-copy print rather than high resolution screens, but Sorkin, Reich and Pizzzimenti (2003) found the accommodative response to a visual display terminal to be the same as printed text. Rosenfield (2011) concluded that there is little evidence to support the proposal that the accommodative demands of a VDT differ from viewing printed materials at the same distance and gaze angle.

Reading text resulted in a reduction in accommodative accuracy that is consistent with Jiang's (1997) modification of Hung and Semmlow's model of accommodation (Figure 1.9), wherein an Accommodative Stimulus (AS; in this case, text on a CRT screen) forms a blur signal which results in an accommodative response (AR). Accommodative Sensory Gain (ASG) represents signal degradation, and it is plausible to suggest that contrast adaptation as shown in Experiment 2 may influence this, and therefore the resultant Accommodative Error (AE). Greater contrast adaptation in myopes may therefore result in greater signal degradation and Accommodative Error (AE), which therefore reduces the system output AR.

5.5. Conclusion

Accommodative lag was similar for emmetropic and myopic participants prior to all adaptation conditions. After reading, myopes showed a significant reduction in accommodative accuracy and a significantly greater accommodative lag than emmetropic participants. There was no significant adaptation effect on accommodative lag after adaptation to the phase randomised stimulus in either refractive error group. Although mean accommodative lag was greater after reading text, the difference in the increase in accommodative lag between conditions 1 and 2 was not significant: future studies should include more participants to determine whether a near task with greater cognitive demand

has bearing on the accommodation response. The implications of these findings are to be considered in more detail in the following chapter, where final conclusions are drawn by collating the findings of all the experiments described thus far.

Chapter 6
Summary and conclusions

6.1 Summary of findings

Chapter 1 discussed the association between prolonged near work, specifically reading, and myopia development. Myopia may result from axial elongation as a result of hypermetropic defocus due to accommodation inaccuracies (section 1.4.2). However, the reason why myopes seem to make poorer accommodation responses compared to emmetropes is unknown. This thesis investigated the changes in contrast sensitivity and accommodation that occur during reading and the influence of cognitive effort on such changes. The results show that myopic participants were more susceptible to contrast and accommodative adaptation effects during reading. Understanding of how reading can engender such changes in different refractive groups will be beneficial in underpinning future studies that aim to prevent myopia.

The current research found greater contrast adaptation and a larger lag of accommodation in myopes after reading. Contrast adaptation has been postulated as an error signal for emmetropisation (Diether et al., 1997; Diether & Schaeffel, 1997; Diether & Schaeffel, 1999). Reduced contrast sensitivity will degrade retinal image quality in myopes who have been shown to be less perceptive of blur as a consequence of greater blur tolerance when compared with emmetropes (Rosenfield & Abraham-Cohen, 1999; George & Rosenfield, 2004). The greater lag of accommodation after reading could result in greater hypermetropic blur that may act as a stimulus to ocular elongation. Myopes who read for prolonged periods might therefore be oblivious to blur in their visual input, despite this having a detrimental effect on their ability to initiate appropriate accommodation responses, which may result in hypermetropic blur and act as a stimulus to myopia development.

6.1.1 Experiment 1: Contrast adaptation to uniform white noise and text stimuli

Contrast adaptation after reading has not previously been investigated in young adults. In this study, contrast adaptation was not found after adaptation to uniform white noise, or text stimuli in young adult emmetropes and myopes. This prevented meaningful comparison of the effects of adaptation between refractive error groups. Furthermore, no specific conclusions can be drawn on the effectiveness of uniform white noise as an adaptor to equalise participants' pre-adaptation contrast sensitivity.

Significant correlations between pre-adaptation $\log_{10}CS$ and the magnitude of change in $\log_{10}CS$ after text adaptation was found only at the text row frequency which suggest that it is appropriate to liken rows of text and inter-text space to a horizontal Gabor grating (Figure

2.7). Scrutinising the weaknesses in the experimental paradigm facilitated the design of all subsequent experiments.

6.1.2 Experiment 2: Myopes experience greater contrast adaptation during reading

Contrast sensitivity was measured before and after reading text on a screen in young adult emmetropes and myopes. Reading induced contrast adaptation at the text row frequency in both refractive error groups and myopic participants incurred more than twice the adaptation of emmetropes. However, contrast adaptation was not significant at the text stroke frequency. The lack of a pronounced narrow-band correlate in the FFT power spectrum (Figure 3.6) and mismatch between FFT analysis and stroke counting results (section 3.4.2) suggests that despite having been used in earlier work, the stroke counting technique proposed by Majaj et al. (2002) may not be an appropriate surrogate for the stroke spatial frequency, or that stroke frequency simply carries insufficient or insufficiently concentrated power to educe adaptation effects. The greater contrast experienced by myopes at the text row frequency after reading warrants further investigation to better understand the relationship between near work and myopia development.

6.1.3 Experiment 3: Adaptation to a phase-randomised, but frequency, orientation, luminance and contrast-matched stimulus

This study was conducted to experimentally examine the mechanisms that underpin contrast adaptation in reading and was conducted following the same experimental protocol as Experiment 2, except the adaptor stimulus was changed to an incomprehensible stimulus. This new stimulus had random phase, but otherwise shared the statistical properties of the text stimulus, and thus retained the superficial appearance of text. No significant adaptation effects were found at either the row or letter stroke frequency for either the emmetropic or myopic participant group. Two hypotheses to explain these findings were proposed: that adaptation to the text stimulus is a consequence of the cognitive effort elicited by active reading, or that veridical phase information must be present in combination with the spatial frequency and orientation properties of a stimulus when investigating adaptation. The impact of cognitive effort in eliciting contrast adaptation correlates well with the association between prolonged near work and myopia (see section 1.3.2).

6.1.4 Experiment 4: Accommodation accuracy before and after reading text and adaptation to phase randomised text

Accommodative accuracy has not previously been compared before and after reading. However, it has been suggested that greater cognitive effort would reduce accommodative lag (Bernsten et al., 2011). In this experiment, emmetropic and myopic participants had comparable levels of accommodative inaccuracy before reading the text stimulus, suggesting that the myopes who participated in this study were not progressing myopes

(Allen & O'Leary, 2006). After reading, myopic participants had significantly greater accommodative lag than emmetropes, and accommodative lag increased significantly in myopes. Adaptation to the phase randomised stimulus did not significantly alter accommodative accuracy in either participant group.

Previous literature has shown that cognitive demand influences accommodative response in myopes (Kruger, 1980; Malmostrom & Randle, 1984; Bullimore & Gilmartin, 1987; Winn et al., 1991; Wolffsohn et al., 2003). However, Bour (1980) suggested that phase shifts are not important for dynamic accommodative responses or microfluctuations. Furthermore, relative phase was not important for the development of form deprivation myopia in chicks, whilst spatial frequency content was (Hess et al., 2006). A significant reduction in accommodative accuracy after reading text, but not adaptation to the phase randomised stimulus, supports the hypothesis that it is the cognitive effort that accounts for the presence or absence of contrast adaptation in Experiments 2 and 3. Additionally, cognitive effort has only previously been investigated with numeracy tasks. The cognitive effort was substantiated with a literacy task in this experiment, which has greater potential to be informative about role of reading in inducing contrast adaptation.

Bullimore and Gilmartin (1988) suggest that greater attention to a task may require more accurate accommodation. However, the results of the present experiment indicate that reading text may make myopes less able to make an accurate accommodation response when compared to emmetropes. However, the influence of cognition cannot be reliably determined due to large measurement dispersion (*viz*., standard error values).

6.2 Study limitations and recommendations for further work

Differences in the magnitude of contrast adaptation and accommodative lag after reading were found between emmetropes and myopes. Despite these differences, it is not possible to determine whether they are a cause or consequence of myopia without undertaking longitudinal studies. This would require a long-term study on a large cohort of emmetropes, specifically children, some of whom might develop myopia and some who remain emmetropic. In this study, the participant cohort for each experiment were not questioned as to the age of onset of their myopia, thereby making it impossible to make inferences concerning the role of genetics and/or environmental factors. Furthermore, previous refraction data was not acquired, which would have enabled it to be determined whether participants' myopia was stable or progressing. Questioning participants to establish what activities they had undertaken prior to experimental participation would have been beneficial to ascertain if there was an overall trend for particular activities undertaken by either refractive error group, either reading text (containing power peaks corresponding to the row

frequency and character stroke frequency) or a more natural visual diet (consisting of 1/*f* spectrum).

6.2.1 Contrast sensitivity

Experiment 1 measured contrast adaptation for five spatial frequencies. In creating an improved measurement protocol in Experiment 2, only the text row width and stroke width frequencies were tested, using appropriate orthogonal controls. Testing additional spatial frequencies in future work would therefore be a natural extension of this study.

Animal studies propose that intermediate spatial frequencies may influence the emmetropisation process (Schaeffel et al., 1999; Schmid & Wildsoet, 1997). Schmid & Wildsoet (1997) proposed that a lack of mid-spatial frequencies in text could be responsible for promoting myopia. FFT of the text stimulus in Experiment 2 showed a distinct lack of power for the mid-spatial frequency text stroke width, as initially determined by the stroke counting technique of Majaj et al. (2002). The selection of spatial frequencies from which to measure contrast adaptation in future studies could therefore be derived from the FFT of adaptor stimuli, rather than using the stroke counting technique, or reverse engineered as in experiment 2 (section 3.2.3). This would ensure selection of the most accurate spatial frequencies as derived from the adaptor stimuli, better supporting the investigation of the role of mid-spatial frequencies in contrast adaptation during reading.

The FFT also revealed that the power of higher spatial frequencies in the text stimulus was rather diffuse, occurring across a wide range of frequencies and orientations, and with significantly reduced power compared to the row frequency (Figure 3.6). It may be inappropriate even to test narrow-band adaptation effects at higher spatial frequencies, given that the power was shown to be distributed across multiple frequencies. It could be that high spatial frequencies (such as those produced by letter strokes) only produce adaptation when seen in unison with low spatial frequencies (text rows); i.e., that it is the interaction between the structures produced at each spatial frequency, rather than power at isolated high spatial frequencies per se, that give rise to adaptation.

Newer alternatives to the adaptive procedures described in section 2.2.5.1 could be utilised to expedite the measurement of contrast sensitivity. The Bayesian adaptive estimation of psychometric slope and threshold developed by Kontsevich and Tyler (1999) has been shown to offer threshold estimation within 23% in less than 30 trials for a typical 2AFC detection task. The quick contrast sensitivity function, qCSF, (Lesmes et al., 2010; Rosén, Lundström, Venkataraman, Winter & Unsbo, 2014) could be incorporated to expedite contrast sensitivity measurement and thereby facilitate inclusion of more spatial frequencies. Like Metropsis (Experiment 1) and the program designed to measure contrast

sensitivity in Experiment 2, the qCSF is a computerised test that provides the precision and flexibility of laboratory psychophysics, but with a significantly reduced testing time comparable to clinical cards and charts. Using typical adaptive procedures, a large number of trials (Farell & Pelli, 1999), typically a minimum of 50-100, are required per spatial frequency condition (Lesmes et al., 2010), whilst the qCSF can achieve reliable estimates of the CSF within 25 trials (Lesmes, Jackson, Wallis & Bex, 2013). Furthermore, qCSF is available as a MATLAB script that could be integrated into the top-up protocol used in Experiments 2 and 3.

6.2.2 Accommodation

Experiment 4 shows increased accommodative lag after both reading and adaptation to a phase-randomised text stimulus. Although the mean difference in the amount of change in lag before and after the two adaptation conditions was large, it did not reach statistical significance. Future studies investigating changes in accommodative lag should include a greater number of participants in an attempt to compensate for the relatively large dispersion (standard deviation) in measurements, and to more conclusively establish the influence of non-optical factors, such as cognition, on accommodative response.

6.3 Contrast adaptation and accommodation

Further analysis of the results for Experiment 2 and 4 show that for emmetropic participants, there was a significant positive correlation between the magnitude of $\log_{10}$CS adaptation at the text row frequency and change in accommodative lag after text adaptation [$r_{(9)}$ = 0.69; p = 0.03 (two-tailed)] which exceeds Cohen's convention for a large effect size (Figure 6.1). The correlation was not significant for myopic participants [$r_{(9)}$ = -0.08; p = 0.82 (two-tailed)] (Figure 6.2). Figure 6.1 illustrates that a reduction in accommodative lag is concurrent with greater $\log_{10}$CS adaptation after reading. Mean contrast adaptation at the text row frequency was >2× in myopic participants; however, this was not significantly correlated with a change in accommodative lag (Figure 6.2).
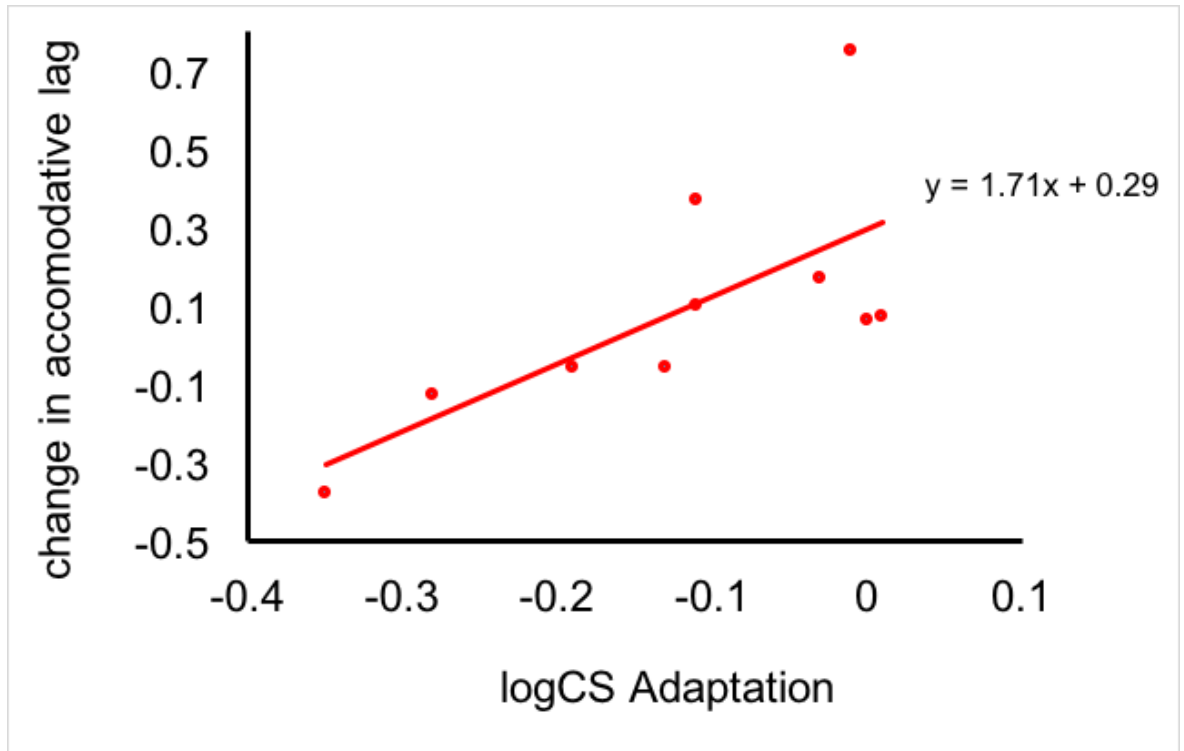
Figure 6.1: Correlation between the magnitude of $\log_{10}$CS adaptation and the change in accommodative lag after reading for emmetropic participants. A negative change in accommodative lag signifies a reduction in lag (more accurate accommodative response), whilst negative contrast adaptation signifies reduced contrast sensitivity.
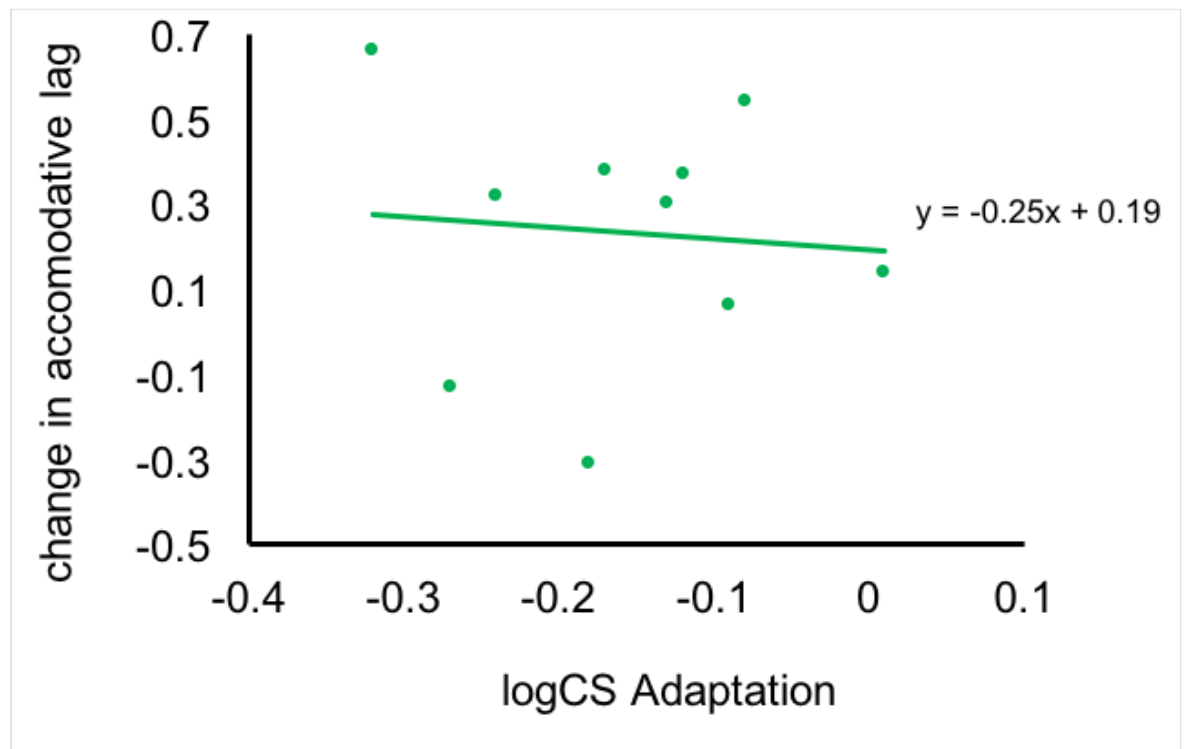
Figure 6.2: Correlation between the magnitude of $\log_{10}$CS adaptation and the change in accommodative lag after reading for myopic participants.

The negative correlation in emmetropic participants could indicate that contrast adaptation drives accommodation accuracy in this group. This manifests as a smaller lag of accommodation as contrast adaptation increases and could be interpreted as a closed-loop

system, whereby the feedback from contrast adaptation mediates the initiation of an appropriate accommodative response. This in turn eliminates a driver to myopia progression (see section 1.9), and is indicative of a homeostatic mechanism. Conversely, in myopes, this feedback breaks down and the system is open-looped: more contrast adaptation is exerted, but this fails to improve accommodative accuracy where higher lag was observed (Figure 6.2), with correspondingly greater contrast adaptation.

Chapter 1.6 describes the neural pathway for the initiation of an accommodative response: utilisation of functional magnetic resonance imaging (fMRI) in future work could be used to probe the cortical location of contrast adaptation in emmetropic and myopic observers and to more accurately determine the correlation between contrast adaptation and accommodative accuracy.

In chapter 4, two hypotheses were proposed to explain why contrast adaptation was measured after reading a veridical text stimulus, but not after adaptation to a –phase randomised stimulus: (1) that contrast adaptation to the text stimulus was as a consequence of the cognitive effort or attention elicited by reading; (2) that the phase component of the stimulus influences the adaptation. Studies have demonstrated that variation in cognitive demand produces significant changes in the accommodative response (Kruger 1980; Malmstrom et al., 1980; Winn et al., 1981; Malmostrom & Randle, 1984; Birnbaum, 1984; Bullimore & Gilmartin 1988; Rosenfield & Ciuffreda, 1990; Rosenfield & Ciuffreda, 1994), whilst it has been suggested that phase shifts are not important for accommodation responses (Bour, 1980), or the development of form deprivation myopia in chicks (Hess et al., 2006). Additionally, sustained attention has been shown to strengthen the magnitude of contrast adaptation (Ling & Carrasco, 2006).

Extrapolation of these findings to the current study, which showed a reduction in accommodative accuracy after reading text, but not adaptation to the phase randomised stimulus, lends weight to hypothesis (1) stated above: that it is cognitive effort rather than stimulus phase characteristics that influences the contrast adaptation measured in Experiment 3. Figure 6.3 illustrates this graphically.

Contrast adaptation

Cognition   Stimulus phase
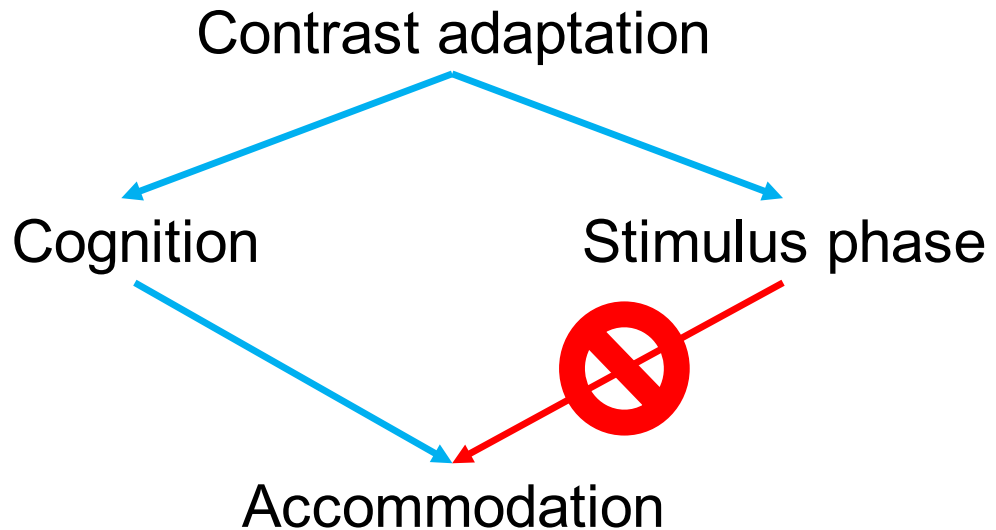
Accommodation

Figure 6.3: Accommodation has been shown to be influenced by cognitive effort whilst stimulus phase characteristics are not believed to be important for accommodative response. This alludes to a stronger role of cognitive demand in eliciting a contrast adaptation response.

As discussed in section 1.3, higher rates of myopia correlate with increasingly competitive and rigorous education systems, which of course entail prolonged periods of reading, further implicating the role of cognitive effort in initiating changes in contrast and accommodative adaptations.

Relating this to the hypothesis presented in Figure 1.12, myopes showed greater contrast adaptation after reading and this reduction in contrast sensitivity may make them less perceptive to blur (section 1.9), due to their higher blur tolerance compared with emmetropes (Rosenfield & Abraham-Cohen, 1999; George & Rosenfield, 2004). Myopes who read for prolonged periods may therefore be oblivious to blur in the text: Wallman and Winawer (2004) speculated that blur adaptation could weaken the accommodation and emmetropisation processes as it would reduce the amount of blur available to act as a stimulus to accommodation. The current study found a larger lag of accommodation in myopes after reading, which would result in greater hyperopic retinal blur. Jiang's (1997) model of accommodation control presented in Figure 1.9 illustrates Accommodative Sesnsory Gain (ASG), which represents signal degradation from sensory aspects of the visual system. Greater contrast adaptation in myopes may therefore result in greater signal degradation and Accommodative Error (AE) which therefore reduces the system output (Accommodative Response AR).

Eleven participants were adapted to both the text and the phase randomised text stimuli, albeit on different occasions. In Chapters 4 and 5, mixed ANOVAs were conducted to compare the magnitude of change in contrast adaptation and accommodative lag between the two conditions. One of the assumptions for this analysis is that there should be independence of observations (i.e. different participants in each group) which in this instance was violated.

A between participants ANOVA is less powerful than a within subjects ANOVA where participants do provide data for two or more groups. This is because within subjects ANOVAs exploit the fact that participants have an in-built innate level of performance, and the aim is to examine the difference in this performance before and after an intervention (i.e., results are paired together, and difference values calculated rather than relying upon absolute performance levels). If a between subjects ANOVA is performed on within subjects data, the per-participant baseline is ignored, and each measurement is treated as having originated from a different person, and thus innate performance level cannot be exploited. In most cases, this would lead to the test being more conservative.

6.4 Clinical significance

Adaptation/reading times were relatively short in Experiments 2, 3 and 4. Typically, humans spend longer than three minutes reading without distant fixations to dissipate any adaptation effect. Ohlendorf and Schaeffel (2009) propose a 5:1 inspection to measurement time ratio for the dissipation of adaptation effects (Chapter 3.4): if a human were to read uninterrupted for one hour, this ratio would indicate that 12 minutes distant fixation is required to eliminate a contrast adaptation effect. The length of time exposed to blur could be important factor in myopia development (Day & Duffy, 2011). Three minutes of optical defocus is sufficient to induce changes in eye growth in animal models (Zhu et al., 2005, Zhu & Wallman, 2009). The greater contrast adaptation and increased accommodative lag after reading in myopes as shown after only three minutes in this thesis could be even more detrimental if the reading task duration were increased or uninterrupted with distant viewing as would be typical in an academic context. The small amounts of defocus experienced during reading could be sufficient to produce a myopigenic change in axial length.

Given that contrast adaptation may result in perceived retinal image degradation (similar to a low level of form deprivation), a prolonged contrast adaptation effect after extended periods of reading could be highly detrimental. Wallman and Winnawer (2004) suggested that the way in which one reads may be an important factor in determining whether near work promotes myopia development. Time spent reading without intermittent distant fixation could therefore be influential in myopia development if contrast adaptation effects are

allowed to persist. This is consistent with the finding that outdoor activities have a protective effect on myopia development (Rose et al., 2008a).

Changes in contrast sensitivity were measured for the text row width spatial frequency. Increasing the spacing between rows of text so that it is larger than the character height will alter the fundamental periodicity of the stimulus (Lunn & Banks, 1986). This will modify the overall duty cycle and therefore spatial frequency of the text row width that may lessen the contrast adaptation effect and reduce the potential myopigenic effect.

Prudent clinical advice should encourage intermittent breaks from reading to allow contrast and accommodative adaptation effects to dissipate. Whilst increased line spacing for printed text might help negate such effects in the first instance.

6.5 Conclusion

The experimental work in this thesis was undertaken to investigate the influence of reading on perceptual adaptations that might engender myopia development. Text stimuli are inherently dominated by low, narrowband and orientation constrained spatial frequencies generated by row of letters and inter-row space. The results presented show myopes to be more susceptible to adaptation to these specific text characteristics as a consequence of active reading. However, there is extensive scope for further work to determine precisely why this is the case and exactly how such changes may be myopigenic.

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PARTICIPANT INFORMATION SHEET

Section A: The Research Project

Title of project: Does visual experience influence accommodative accuracy and the maintenance of a clear retinal image?

Purpose of study: The study will investigate the effect different close targets have on your eyes ability to detect blur. We will measure how accurately your eyes respond to blur, to improve understanding of an association between blur detection and the progression of myopia (short sight).

Who is organising the research? The principle investigator is Mr. Colm McGonigle, Coslett 308a, Anglia Ruskin University, East Road, Cambridge, CB1 1PT, colm.mcgonigle@anglia.ac.uk, 0845 196 2106. The research is funded by Anglia Ruskin University, and is being carried out within the Vision & Eye Research Unit (VERU) at the Department of Vision & Hearing Sciences.

What will happen to the results of the study – The results of the study will be analysed then presented in my PhD thesis and at a scientific conference. Any information obtained during this study that may identify you will remain confidential and will be disclosed only with your permission. When the results of the study are published you will not be identified by name.

Section B: Your Participation in the Research Project

Why you have been invited to take part – We have invited you to take part as we need to compare people with myopia to those with normal sight.

Whether you can refuse to take part – You are able to refuse participation.

Whether you can withdraw at any time, and how – You are able to withdraw from the study at any point by simply completing the lower section of your consent form and handing it to the researcher.

What will happen if you agree to take part (brief description of procedures/tests) – We will take measurements of the size, focussing and shape of your eyes. We will blur your vision temporarily with the induction of plus powered spectacle lenses over your normal spectacle correction, then measure your contrast sensitivity using Metropsis CSF test. On a separate occasion we will blur your vision with the use of a cyclopentolate eye drop to relax your eyes accommodation. This drop is used routinely in eye examination, particularly when examining children. The eye drop will dilate your pupil and will make your near vision blurry of the remainder of the day and you may be more sensitive to bright light. We therefore recommend that you do not drive, ride a bicycle or operate heavy machinery for the remainder of the day. The eye drop will take around 30 minutes to work and up to 24 hours to fully wear off.

There is also a very small risk of acute angle closure glaucoma as a side effect of these drops. The signs and symptoms of this are a painful red eye and seeing haloes around lights. The initial part of the examination will include tests to highlight those people who may be at risk of this condition, thereby excluding them from participating. If you did experience the aforementioned symptoms, you should contact us immediately or attend hospital accident and emergency department

1.   What will happen if you agree to take part (brief description of procedures/tests)

2.   Whether there are any risks involved (e.g. side effects from taking part) and if so what will be done to ensure your wellbeing/safety

3.   Agreement to participate in this research should not compromise your legal rights should something go wrong

4.   Whether there are any special precautions you must take before, during or after taking part in the study

5.   What will happen to any information/data/samples that are collected from you

6.   Whether there are any benefits from taking part

7.   How your participation in the project will be kept confidential

YOU WILL BE GIVEN A COPY OF THIS TO KEEP,
TOGETHER WITH A COPY OF YOUR CONSENT FORM

Appendix B:

PARTICIPANT CONSENT FORM

NAME OF PARTICIPANT:

Title of the project: Does visual experience influence accommodative accuracy and the maintenance of a clear retinal image?

Main investigator and contact details: Colm McGonigle, email:colm.mcgonigle@anglia.ac.uk

Members of the research team, Dr. Peter Allen, Dr Ian van der Linde, Prof. Shahina Pardhan, Prof. Ed. Mallen.

1. I agree to take part in the above research. I have read the Participant Information Shee which is attached to this form. I understand what my role will be in this research, and all my questions have been answered to my satisfaction.

2. I understand that I am free to withdraw from the research at any time, for any reason and without prejudice.

3. I have been informed that the confidentiality of the information I provide will be safeguarded

4. I am free to ask any questions at any time before and during the study.

5. I have been provided with a copy of this form and the Participant Information Sheet.

Data Protection: I agree to the University[1] processing personal data which I have supplied. I agree to the processing of such data for any purposes connected with the Research Project as outlined to me*

Name of participant (print)…………………………Signed……………….……Date………………

Name of witness (print)…………………………..Signed……………….……Date………………

YOU WILL BE GIVEN A COPY OF THIS FORM TO KEEP

If you wish to withdraw from the research, please complete the form below and return to the main investigator named above.

Title of Project:

I WISH TO WITHDRAW FROM THIS STUDY

Signed: _____   Date: _____

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[1] "The University" includes Anglia Ruskin University and its partner colleges

Appendix C: Vision Research publication

https://www.sciencedirect.com/science/article/pii/S0042698916000134?via%3Dihub