Applications of holograms for spherical refractive error measurements

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Applications of Holograms for Spherical Refractive Error Measurements

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Thesis/Dissertation Sheet

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Many practitioners are aware that some patients (especially young myopic subjects with their high accommodative amplitude) tend to accommodate when seated behind a refractor or when looking through instruments such as microscopes. This research revealed that holograms possess the useful ability to inhibit reflex accommodation. It was fascinating to observe young subjects having difficulty exercising accommodation and focusing on the closer targets in the hologram. The research also revealed that there is a medium correlation between these subjects and myopic progression, suggesting a possible predictor for myopic progression.

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Dedication and acknowledgement

In memories of my late paternal grandparents, maternal grandparents and mother-in-law, all of whom left fingerprints of grace in my life. They were my inspiration and live on in my heart.

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Abstract

Subjective refraction is part of an optometrist’s daily routine to elicit and correct the refractive error of patients. Refraction is often carried out in the clinic using test charts at 4 m or 6 m distances. Often in small rooms, practitioners use mirrors to extend the distance at which the chart is presented. Room illumination, chart luminance, testing distance and letter arrangements/layout will, therefore, vary between clinics and locations. The conditions when testing vision and measuring refractive error subjectively thus vary among locations, and this affects the results of the tests when performed on a patient at different locations. Furthermore, different projector charts with multiple letter configurations are still in mainstream use, but letter contrast may also differ between visits as the projector bulb or lens may attract dust and dirt, reducing the contrast over time.

Holograms are unique because they literally ‘freeze time’ by capturing the original scene and storing it in a glass plate. Through a process known as ‘reverse phase-conjugation’, clinicians are able to ‘reverse time’ to recreate the same initial scene with all 3D features. In this thesis, three transmission phase holograms were successfully recorded that were useful for vision testing. The vision and spherical refractive errors of some subjects were measured using these holograms and compared with the results from conventional methods currently used in optometry clinics. The results showed that the holographic method is a suitable alternative to conventional method when used to measure spherical refractive error. However, as expected when using monochromatic illumination, vision measured using the hologram was about 0.50 logMAR greater (worse vision) than vision measured through conventional methods.

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there is a medium correlation between these subjects and myopic progression, suggesting a possible predictor for myopic progression.

Publications arising during candidature

Avudainayagam, K. V., Avudainayagam, C. S., Nguyen, N., Chiam, K. W., & Truong, C. (2007). Performance of the holographic multivergence target in the subjective measurement of spherical refractive error and amplitude of accommodation of the human eye. *J Opt Soc Am (A), 24*(10), 3037-3044.

Nguyen, N., Avudainayagam, C. S., & Avudainayagam, K. V. (2012). An experimental investigation of the vision of hyperopes and myopes using a hologram. *Biomed Opt Express, 3*(6), 1173-1181.

Nguyen, N., Avudainayagam, C. S., & Avudainayagam, K. V. (2013). Role of Mandelbaum-like effect in the differentiation of hyperopes and myopes using a hologram. *J Biomed Opt, 18*(8), 85001.

Avudainayagam, K. V., Avudainayagam, C., & Nguyen, H. N. (2015). A Test for Progressive Myopia and the Role of Latent Accommodation in its Development. *Int J Ophthalmol Clin Res, 2, 2*.

Manuscripts submitted or in press

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Nguyen, N. H. N., Golebiowski, B., Roy, M. (2016). *Involuntary accommodation to a multi-vergence target.* Manuscript submitted for publication.

Nguyen, N. H. N., Roy, M. (2016). *Hologram inhibits the accommodation of Young subjects*. Manuscript submitted for publication.

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Introduction and literature review

Chapter 1

1.1 Ametropia and simple refractive error

The human eye is one of the most sophisticated optical systems constituted of multiple refracting surfaces which transform all the optical information from the outside world on the light sensitive layer at the retina.

The human eye has the capacity to focus on objects that are located over a range of distances. This is possible because the eye can adjust the focusing power of its lens by changing the shape of its lens. As the divergence of the rays from nearby objects is larger than the divergence of the rays from distant objects the lens becomes more convex (rounded) when looking at nearby objects thus increasing the focusing power of the eye. The mechanism by which the eye changes its focusing power using muscular action is called accommodation.

An eye with minimal accommodation that could focus a distant object at the centre of the macula M' is referred to as being emmetropic. Macula (M') is an oval-shaped pigmented area near the centre of the retina of the human eye (Figure 1.1). In an emmetropic eye, the second focal point of the reduced eye (F_e') coincides with the centre of the macula (M').

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Figure 1.1. A parallel pencil of light rays is focussed on the retina in an unaccommodated (or minimally accommodating) emmetropic eye. F_e' coincides with the centre of the macula.

An eye that is unable to focus a distant object onto the retina is therefore referred to as being ametropic. Since the optical image is focussed away from the retina, the retinal image is blurred resulting in unclear vision and reduced visual performance. The correction for ametropia is simple and is achieved through optical means (spectacle lenses, contact lenses, etc.) or by interventional techniques to alter the shape of the cornea (e.g. laser refractive eye surgery, ortho-keratology) or by changing the power of the crystalline lens (e.g. intraocular lenses, lens implants etc.).. Although the correction can be simple, over 100 million people around the world are still visually impaired because of uncorrected refractive error (Bourne et al., 2013).

Ametropia is divided in two main categories: Spherical ametropia and astigmatism. In spherical ametropia, the eye's refractive system is symmetrical about the optics axis so that there is relatively equal power along all the meridians. In astigmatism, the eye's refractive system is not symmetrical about the optics axis, so different powers exist along the different meridians.

1.2

This thesis will only discuss spherical ametropia (myopia and hyperopia).

Types of spherical ametropia

1.2.1 Myopia

Myopia (near-sightedness, short-sightedness) is a type of refractive error where a distant object is focussed anterior to the retina under minimal accommodation (Figure 1.2). This is either from an eye with a relatively long axial length or an eye with a relatively greater combined refractive power (Rosenfield, 2006). Aristotle (384–322 BC) was the first to describe near-sightedness (Goldschmidt, 1968), but the term myopia was coined by Galen (131–201 AD) from the words *myein* (meaning ‘to close’) and *ops* (mean ‘eye’). Galen observed that people suffering from near-sightedness had to squint or partially close their eyes to get better vision (Benjamin, 2006). However, Galen incorrectly assumed the cause of myopia was from a lack of visual spirits called ‘pneuma’ that would fill up the anterior chamber. In a person lacking this apparent ‘pneuma’, there was insufficient pneuma to leave the eye and reach a distant object; hence, the blurry vision. We now know this is incorrect.

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Figure 1.2. A parallel pencil of light rays is focussed anterior to the retina in a myopic eye with minimal accommodation. The second focal point F_e' lies in front of the retina.

Researchers over the past 150 years have developed numerous different types of classification systems for myopia. Grosvenor (1987) reviewed the many classification systems and was able to classify myopia under broad categories, which will be discussed below (Grosvenor, 1987).

1.2.1.1 *Classification by the rate of progression*

Donders classified myopia according to its rate of progression, and he described myopia as being stationary, temporarily progressive, or permanently progressive (Donders, 1864). Stationary myopia, according to Donders, is a low-level form of myopia (-1.50 to -2.00 D) that typically starts during early development. The myopic progression for individuals affected by this condition is usually 'stationary' during adulthood and can even reduce with old age. Temporary progressive myopia, on the other hand, typically starts during early teenage years, and the myopia progresses into the late 20s. Permanently progressive myopia progresses rapidly until the ages of 25 to 35, after which the myopic progression starts to slow down. Donders made many incorrect interpretations to certain observations about myopia. For instance, in his classification of stationary myopia, he associated the reduction of myopia with age as being due to the increased depth of focus from age-related pupillary miosis. He also reported that if an eye was previously 'normal', myopia would rarely develop after the age of 15, and that it was virtually impossible to develop this condition after the age of 20. We now know that these facts are false, since pupil miosis may improve vision but does not change the refractive error, and myopia can develop in adults (see late-onset myopia classification below).

1.2.1.2 *Classification according to anatomical features of the myopia*

Borish also classified myopia according to certain anatomical features (Borish, 1970). According to his system of classification, myopia could either be:

1) axial in nature whereby the eye is too long for its refractive power, or

2) Refractive whereby the refractive power of the eye is greater than the axial length of the eye. Furthermore, Borish subdivided refractive myopia into three possibilities:
    a. Index myopia, where the refractive indices of one or more ocular media is anomalous (usually with a higher refractive index).
    b. Curvature myopia, where the dioptric power of the eye is greater than usual from a reduced radius of curvature of one or more refractive surfaces.
    c. Anterior chamber myopia, where the refractive power of the eye is greater because of a relatively greater anterior chamber depth.

1.2.1.3 *Classification by the degree or level of myopia*

Hirsch (1950) examined 562 eyes with at least 1 D of myopia, with subject aged between 18 and 60. Hirsch separated the subjects according to gender, and then categorised subjects into three groups (alpha, beta, gamma) according to the severity of their myopia (Hirsch, 1950). The study found that the alpha group had a normal distribution curve with a theoretically assumed peak of +0.50 D. Using the same analysis, the beta group also had a normal distribution curve with a peak of -4 D. The gamma group was described as being pathological, malignant, degenerative or congenital, with a myopic range of -9 to -15 D. Subjects making up the gamma group had an unusually high refractive error and the sample was too small to determine whether the distribution followed a normal curve.

According to a study led by Sorsby in 1957 (Rosenfield, 2006), the group investigated the refractive error of 341 eyes between the ages of 20 and 60. They found that 95% of refractive errors from the study were within ±4 D. They also found that the biometric component values for refractive errors within ±4 D were not significantly different to those of an emmetropic person. The group concluded that the aetiology of myopia less than -4 D was different to those with myopia greater than -4 D. The group also concluded that low ametropia was due to an incorrect correlation between the individual ocular components resulting in a refractive error, rather than any particular ocular component being anomalous.

Classifying the myopia according to severity can be useful since most patients would like to know their level of ametropia, whether this level of ametropia is significant, and how much this ametropia can affect their vision and everyday life. However, this classification does not take the patient's age into consideration. Unless an individual is born with myopia, the degree of myopia typically starts from a low level, and can develop with age. The refractive error should also take the patient's age into account, since the age would have a bearing on when the myopia might stabilise. In other words, having -2 D of myopia at 5 years of age is more disconcerting than -2 D in a 30-year-old.

1.2.1.4 *Physiological or pathological myopia*

Physiological (non-pathological) myopia was defined as myopia caused by an incorrect correlation between the ocular components of the eye (Curtin, 1985). On the contrary, pathological myopia was defined as myopia with ocular structure (or structures) deviating from normal (Duke-Elder & Abrams, 1970). Pathological myopia could also be described as degenerative (or malignant), usually because of the associated degenerative changes when the myopia reaches -6 D or more (lower magnitude). However, using a magnitude to classify pathological myopia is unsuitable, since low myopia may also exhibit degenerative changes (Duke-Elder & Abrams, 1970) and high myopia (-7 D) may have no observable pathological changes (Rosenfield, 2006).

1.2.1.5 *Hereditary and environmentally-induced myopia*

The debate of whether myopia development is hereditary or environmentally induced has persisted for more than 400 years. Kepler (1604) suggested a possible association between sustained near-work and myopic development, yet evidence for this claim is inconclusive (Rosenfield, 2006). Unless a newborn has myopia (congenital myopia), it is difficult to determine whether the cause of myopia in a patient is from hereditary or environmental factors. Evidence suggests that the cause of myopia is multifactorial (Goldschmidt, 2003; Lee, Lo, Sheu, & Lin, 2013; Wu & Edwards, 1999).

1.2.1.6 *Classification according to theories of myopic development*

There are three major theories that could explain the aetiology of myopia (McBrien & Barnes, 1984):

- the biological-statistical theory
- the use-abuse theory
- the theory of emmetropisation.

The biological-statistical theory was proposed by Steiger (1913), and suggests that the existence of refractive errors forms a biological continuum that ranges from high hyperopia through to high myopia (Rosenfield, 2006). In this sense, myopia exists from the natural variation of the ocular physiological component, and could be considered a variation of normal. However, this theory may not be very popular since studies from Stenstrom (1948) and Sorsby et al. (1957) found that refractive errors do not follow a normal distribution (Rosenfield, 2006).

Crohn proposed the use-abuse theory where he suggested that myopia was the result of an adaptation to the abuse of the eyes during prolonged and sustained near tasks (Rosenfield 2006). He examined over 10, 000 German school-children and found that most young children started with relatively little myopia, and that the prevalence of myopia would increase with age. Crohn concluded that the prevalence of myopia increased because of a greater level of sustained near-work that often comes with age and education. To confirm this theory, there are independent researchers that suggested occupations with greater near-work demand also resulted in a greater prevalence of myopia (Adams & McBrien, 1992; Goldschmidt, 1968; Zylbermann, Landau, & Berson, 1993). Further credence for this theory exists in animal studies where Young (1961) found that restricting the vision of monkeys to only a near environment resulted in increased levels of myopia (Grosvenor, 1996; Rosenfield, 2006). Furthermore, when the Eskimo population was introduced to education, this resulted in greater near-work and the prevalence of myopia increased (Alsbirk, 1979; Richler & Bear, 1980a, 1980b; Young et al., 1969). However, other factors may have also been in play because studying the indigenous Eskimo villages in the undeveloped and remote Artic and sub-Artic showed a higher than average prevalence of myopia, even though the community were not exposed to the increased demands of near-work (Alward, Bender, Demske, & Hall, 1985). Other possible factors such as intelligence and a western diet may have partially contributed to the increased prevalence of myopia in the population (Goldschmidt, 1968; Saw et al., 2004).

The prevalence of emmetropia is substantially higher than predicted by the biological-statistical theory. This suggests that there is an active process towards emmetropia, also known as emmetropisation. Instead of the eye's components growing independently of each other, there is a possible coordinated and correlated growth of the ocular structures for the eye to become emmetropic and therefore, optimise visual acuity (Hofstetter, 1969; Van Alphen, 1961).

1.2.1.7 *Classifying myopia by the age of myopia onset*

Myopia could also be classified according to the age of the myopia onset. According to a review by Grosvenor (1987), myopia could be categorised as:

- congenital myopia whereby the myopia exists from birth
- youth-onset myopia whereby the myopia starts to develop between 6 years of age and the early teenage years
- early adult-onset myopia whereby the myopia starts to develop between the ages of 20 and 40
- late adult-onset myopia whereby myopia onset occurs after the age of 40.

The ocular components of the eye tend to stabilise by various ages, with the eye length, in particular, stabilising by 13 years of age (Larsen, 1971; Rosenfield, 2006), and many of the other ocular components stabilising by ages 13 to 15 (Grosvenor, 1994; Grosvenor & Scott, 1994). The refractive error of most children has been found to stabilise around the ages of 15 (Brown, 1938, 1942; Goss & Winkler, 1983; Slataper, 1950) or 16 (Morgan, 1958). However this is not always the case, since myopia development can also occur at a later age after the cessation of body growth (Goldschmidt, 1968). In recent times, the prevalence of myopia has increased dramatically, and support for the use-abuse theory for myopia development has become more common (French, Morgan, Burlutsky, Mitchell, & Rose, 2013).

1.2.1.8 *Other myopias*

Refractive shift due to low luminance

Night myopia, twilight myopia or the dark focus, are phenomena of becoming myopic during levels of low luminance, and was first reported by an astronomer, Reverend Maskelyn, in 1789. The refractive shift was generally accepted to be caused by accommodation of up to 1 D in young individuals (Artal, Schwarz, Canovas, & Mira-Agudelo, 2012; Epstein, 1982; Rosenfield, 2006). This was discussed further Chapter 1.

Although a lot of research into myopia has been focused on understanding its aetiology, development and pathological effects on the eye, the myriad of classification systems and theories of development show that researchers are still baffled by this condition. As myopia becomes more prevalent in certain regions of the world (Grosvenor, 2003; Holden, 2004; Junghans & Crewther, 2005; Morgan, Rose, Smith, & Mitchell, 2004; Morgan, Speakman, & Grimshaw, 1975; Mutti & Bullimore, 1999; Park & Congdon, 2004), the cost to society and the individual's quality of life are at stake, especially when the ametropia is of a reasonable degree and is uncorrected.

1.2.2 Hypermetropia (hyperopia)

Hypermetropia, or hyperopia, is the ocular condition where the eye has relatively insufficient refractive power to focus a distant object onto the retina. This can come about from either the eye having a relatively short axial length or a reduced dioptric power of the ocular refractive elements.

In a hyperopic eye with minimum accommodation, the optical image of a distant object is focussed posterior to the retina (Figure 1.3).

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Figure 1.3. A parallel pencil of light rays would focus behind the retina in an unaccommodated hyperopic eye. The secondary focal point F_e' lies behind the macula.

Hyperopia was first mentioned as early as 1623 when Levene described the poor effect on vision when he stated, ‘sometimes the sight of old people is so greatly weakened that they are even unable to see far away and many need to have glasses to see at a distance’ (Rosenfield, 2006). Hamberger, in 1696, also discussed how the young and even babies could be born with ‘presbyopia’ (Borish & Benjamin, 2006; Duke-Elder & Abrams, 1970). Hyperopia can reduce vision for distance and/or near, depending on the magnitude of the hyperopia and accommodative ability of the eye to overcome the refractive error. Since the accommodative demand is greater for closer objects, near vision is generally affected more. Probably for this reason, early researchers had difficulty understanding the difference between hyperopia and presbyopia, since both can cause poorer near vision (Rosenfield, 2006).

Donders was credited as being the first to correctly differentiate hyperopia and presbyopia as being two separate refractive conditions of the eye (Donders, 1864). However, unlike myopia, hyperopia was of less interest to researchers, probably because of its more stable nature when compared to myopia (Grosvenor, 1971). Nonetheless, Borish & Benjamin (2006) classified hyperopia according to:

- anatomical features
- the degree of hyperopia
- physiological and pathological hyperopias
- the action of accommodation.

1.2.2.1 *Classification by anatomical features*

Similarly to myopia, hyperopia could be either:

1) axial, whereby the axial length is too short for the refractive power of the eye, or
2) refractive, whereby the refractive power of the eye is too weak relative to the eye's axial length. Refractive hyperopia has been further categorised by Borish as:
    - Index hyperopia, whereby the refractive indices of the ocular components are anomalous (usually lower).
    - Curvature hyperopia, whereby the radius of curvature of one or more of the refractive elements is higher than usual, resulting in a reduced refractive power of the eye.
    - Anterior chamber hyperopia, in which the depth of the anterior chamber is reduced, reducing the effective refractive power of the eye.
    - Other factors resulting in a lower refractive power of the eye, such as the absence of a refractive element (such as aphakia), or displacement of a refractive element (such as a laterally displaced crystalline lens).

1.2.2.2 *Classification by the degree of hyperopia*

According to Borish & Benjamin (2006), hyperopia can be classified according to the magnitude of the refractive error as follows:

low hyperopia	(0.00 to +3.00 D)
medium hyperopia	(+3.12 to +5.00 D)

- high hyperopia (> +5.00 D).

Unlike myopia, hyperopia can be overcome through accommodation. This classification provides a magnitude of the refractive error, which is good for monitoring purposes. However, it does not give the practitioner any indication as to whether the patient is able to cope with the refractive error. For example, a young child can easily overcome low to medium hyperopia, but an elderly patient may have trouble focussing in the distance with low hyperopia. A more useful classification is to categorise the hyperopia according to the action of accommodation (next section).

1.2.2.3 *Classifying hyperopia by the action of accommodation*

A hyperope who is constantly accommodating for both distance and near may experience asthenopic symptoms. It is, therefore, useful to classify hyperopia according to the action of accommodation. According to Borish & Benjamin (2006):

- Latent hyperopia is the amount of hyperopia that is masked by the ciliary tone of the eye and which could only be measured through the use of a cycloplegic agent.
- Manifest hyperopia is the amount indicated by the maximum plus lens that still provides for optimum distance visual acuity. It is usually the hyperopia that is measured by the clinician.
- Total hyperopia is the sum of both the latent and manifest hyperopia. Total hyperopia can be further categorised into:
    - Facultative hyperopia is the hyperopia masked by accommodation, but which is measurable with non-cycloplegic refraction.
    - Absolute hyperopia is the amount of hyperopia still uncorrected after the patient exercises accommodation. As an example, if a +5.00 D hyperope could only partially correct his/her refractive error by accommodating +2.00 D, then the absolute hyperopia would be +3.00 D.

1.2.2.4 *Classification as physiological and pathological hyperopias*

As discussed previously in section 1.2.1.4 with myopia, hyperopia could also be classified as physiological or pathological. Physiological (non-pathological) hyperopia is when the hyperopia is still within the normal limits of biological variation. On the contrary, pathological hyperopia has ocular components that might be outside the range of 'normal.' Examples include space-occupying lesions or central serous retinopathy that both can result in the shortening of the eye's axial length. Another example is the flattening of the cornea in conditions such as corneal plana.

The previous sections have discussed the types of spherical refractive errors and how these refractive errors can compromise vision and/or induce asthenopic symptoms. The next section discusses the various methods to measure and correct spherical ametropia.

Subjective refractive error determinants

1.3

1.3.1 Historical methods of subjective refraction

Please refer to Appendix A for a historical review of subjective refraction methods.

1.3.2 Modern subjective refraction and refractor head

The subjective refraction is the term used to describe the method of successive lens changes in front of an eye. Depending on the reported perceptual changes in the patient's vision, an appropriate lens is introduced to arrive at the most positive lens combination that gives the maximum visual acuity (Polasky, 1991). In modern times, subjective refraction is often performed using a trial frame and trial lenses or by using a refractor. In practice, subjective refraction is a whole lot more complicated, as the practitioner must also assess the visual needs of the patient, and then come to prescription to address these needs (Stein, Slatt, & Stein, 1992). A full subjective refraction also involves determining the ocular astigmatism as well as a binocular balance of the two eyes.

Although the modern design of the refractor was introduced by Giraud-Teulon, it was up to an American inventor, De Zeng, to design significant changes to the refractor (patented, 1909 and 1924). Many features of De Zeng's design included a more compact design, the possibility to perform near tests, the incorporation of certain accessories such as Maddox rod, rotary prism, cross cylinders, as well as simultaneous cylinder axis changes (Lang, 1980).

The modern refractor permits rapid interchange of the lens by rotating discs (spherical lens power change) or knobs (cylindrical power and axis change). Figure 1.4 shows a photo of such a refractor and its features (Table 1.1).

The refractor is still in mainstream use in the United States as well as in Australia, with automated refractors becoming more commonly used.

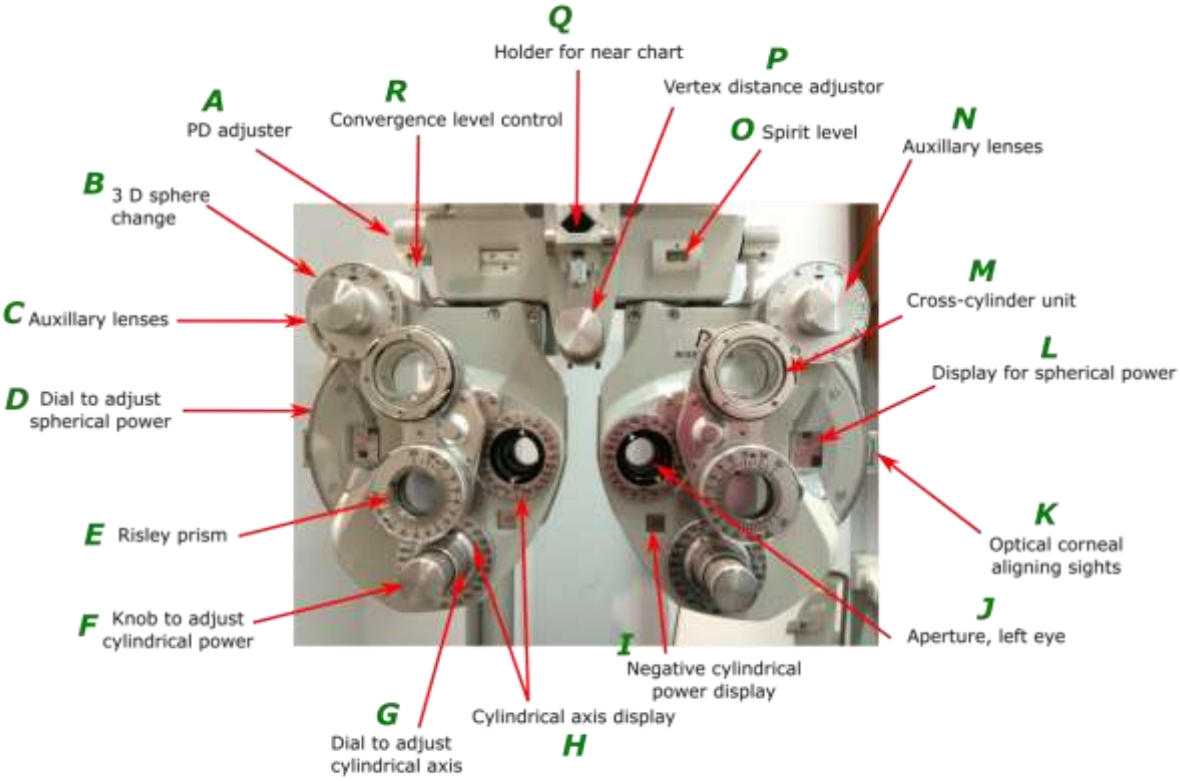

Figure 1.4. A refractor for the purpose of performing subjective refraction.

Table 1.1. Features of the refractor in Figure 1.7.

Label	Feature	Comments
A	Inter-pupillary distance (PD) adjuster	Changes the distance between the apertures to account for differences in patient's PDs. This model adjusts for PDs between 48 mm to 75 mm
B	3 D sphere change or strong sphere change	Makes lens changes in 3 D steps
C	Auxiliary lenses	Includes occluder ±0.50 fixed cross-cylinder dissociating prisms (6 base up prism, 10 base in prism) Pinhole +0.125 DS lens +1.50 D retinoscopy working distance lens (usually with low reflection coating) red lens green lens Maddox Rod (horizontal, vertical) 2x open aperture (located at opposite ends of dial for convenience)
D	Spherical power disc	Changes spherical lens power in 0.25 DS increments
E	Rotary or Risley prism unit	Continuously variable prism

Label	Feature	Comments
		power
F	Cylindrical lens dial	Changes negative cylindrical power in 0.25 DC steps. Power ranges from Plano to -6.00 DC. There is usually a 0.12 DC accessory that is attachable to permit refinement. 2.00 DC accessory that is attachable to extend the power range to 8.00 DC.
G	Cylindrical axis dial	Continuous axis change with 5° axis scale.
H	Cylindrical axis display	Displays cylinder axis (5° scale)
I	Cylindrical power display	Displays the negative cylinder power
J	Eye aperture	Aperture for patients to look through
K	Corneal aligning sights	The zero point assumes 13.75 mm from the apex of the cornea. Each hash mark represents 2mm distance
L	Spherical power display	Positive lens powers are in black. Negative lens powers are in red.

Label	Feature	Comments
M	Cross cylinder unit	To perform the Jackson cross-cylinder test. Standard cross cylinder supplied is 0.25 DC. Able to have substitutes of 0.37 DC and 0.50 DC
N	Left auxiliary lenses	Usually the same as right side except for the following: 10 base in prism, Green lens Red Vertical Maddox lens Or White Maddox lens Polarising lens (45°, 145°)
O	Spirit level	Ensure refractor is level
P	Forehead adjuster	Vertex distance control
Q	Clamp for near chart	Accepts the near chart rod to permits near testing by addition of a near chart
R	Vergence lever	To compensate for the natural convergence of the eye during near tests

The refractor is useful since it permits numerous tests for refractive error measurements and binocular vision assessments to be performed quickly. Proper training is therefore necessary to fully utilise all the features of the refractor. For an accurate refractive error determination, the manner in which the practitioner performs the refraction is important for controlling and minimising any accommodation by the patient. Binocular methods of refraction are generally considered superior to monocular methods (Rabbetts, 2007). Furthermore, the refractor was intended for use in a consultation or examination room, and is difficult to carry between different locations. Unlike the trial frame with trial lenses, the refractor does not simulate the natural position or posture of the patient during everyday tasks. The effect may be exacerbated for higher refractive errors.

When using the refractor for subjective refraction, for strong powers (> 10 D), the indicated lens power of the refractor may not be the true lens power because of possible imperfect power addition of the lenses combination of the refractor (Borish & Benjamin, 2006). Also, the final spectacles worn by the patient may be different in terms of pantoscopic angle, face-form of the lenses in the refractor, and vertex distance. The use of the refractor generally does not induce proximal accommodation (Miller, Wesner, Pigion, & Martin, 1984) unless the practitioner is not vigilant to control and minimise inappropriate accommodation. It appears knowledge of the close testing object can be a strong cue for proximal accommodation during refractor use (Kotulak, Morse, & Wiley, 1994). However, many of these limitations also exist for other spherical refractive error methods (as will be discussed further below).

Point-spread function (PSF) Refractor (Vmax Vision, Maitland, Fla) uses a PSF target instead of a standard letter chart and the device could measure refractive error in 0.05 D steps instead of the usual 0.25 D step with a refractor. Tests comparing the refractive endpoints of the PSF refractor and a manual refractor, have shown that over ninety percent of test subjects have equal or improved visual acuity with the PSF refractor (Gordon & Morrill, 2013; Lai, 2014). The same tests have also shown that ninety percent of subjects preferred the PSF refractor because the test is both faster and easier to perform.

1.4 Subjective refraction (procedure)

This section discusses one possible method for monocular subjective refraction.

1.4.1 Setup

Subjective refraction can be performed simply using a letter chart and trial case. However, modern subject refractions are often done inside a consultation (examination) room using a refractor head and an electronic or projector chart. Considerations for this setup include:

i - An appropriate testing distance (usually 6m / 20 feet).

ii - Appropriate chart positioning for patients comfort (at their eye level) but also convenient for practitioner to manipulate.

iii - If the testing distance is elongated with a mirror, said mirror needs to be suitably large to enable view by patients of different heights. The frame of the mirror also needs to merge with the surroundings to reduce accommodation to the frame of the mirror.

v - Room illumination needs to be comfortable. Refraction performed in the dark will dilate the pupils and may induce some peripheral aberrations. Refraction in a bright room will induce pupil miosis and increase the depth of focus on the eye. Refraction should take these considerations into account.

1.4.2 A monocular subjective refraction routine (Simple refractive error)

Subjective refraction is usually preceded by an objective method, such as retinoscopy or auto-refraction. In this case, it becomes a method of refinement. Assuming the practitioner is starting from scratch (no objective estimate), then the steps below is one possible routine:

1) Unaided vision is measured and used as a guide to the magnitude of the refractive error. For example, while testing one eye, if unaided vision is 6/9 (20/30), then it indicates a relatively low refractive error. The patient's age should be used to consider the possible type of ametropia. Unaided vision of 6/9 (20/30) could indicate absolute hyperopia in early presbyopic patients, high hyperopia in a young patient or a low

myopic patient. Since the unaided vision is relatively good, a low positive sphere (e.g., +0.50 DS) is given to the patient while he/she is looking at a distant letter chart. If vision improves or remains the constant, then another + 0.50 DS could be given until vision worsens. If vision worsens at any stage, then negative lenses (such as -0.25 DS or -0.50 DS) is given to refine and obtain the clearest vision.

i) Since giving more negative lenses than necessary may cause the patient to accommodate, care should be taken to minimise over-minusing when possible.

ii) If vision is poor, lenses can be given to the patient in larger increments or steps.

iii) The endpoint to refraction is usually the most positive lens (or least negative lens) that still provides the 'best' visual acuity.

iv) Check-tests are used to confirm the endpoint, such as adding positive lenses with the expectation of blurring vision. Usually, this test is done with a +1.00 DS with the expectation of blurring vision back to the 6/18 (20/60) line (Rabbetts, 2007).

v) Some hyperopic patients may have trouble relaxing their accommodation. It might be useful to apply the +1.00 DS check test, and to then reduce the fog in 0.25 DS step until the best vision is attained.

vi) Some patients may accommodate when given a high level of fog (1.50 D to 2.0 D) since vision at this level of fog is too fuzzy to effectively control accommodation.

vii) A cycloplegic agent may be necessary to inhibit the accommodation of the
1.5 eye when latent hyperopia is suspected.

Subjective optometers

The term optometer was first used by William Porterfield to describe any instrument used to measure the refractive error without the need for trial lenses. Subjective optometers rely on a subject’s feedback and are dependent on the subject’s co-operation.

The earliest optometer known, in principle, is probably the Scheiner’s disc with multiple pinholes. Usually, a Scheiner disc consists of an opaque disc pierced with two holes, each of about 1.0 mm diameter with their centres 2–4 mm apart. This separation must always be less than the pupil diameter. The disc is placed close to the eye and is carefully centred (with respect to the pupil). The disc permits only two narrowly separated pencils to pass through into the eye. The subject looks at a small distant spotlight. An emmetropic eye will see a single spot (Figure 1.5a), whereas an ametropic eye sees two spots. In a hyperopic eye, the distant object would focus behind the retina, so rays reaching the retina are uncrossed (Figure 1.5b). On the contrary, in a myopic eye, the rays would be crossed at the retina (Figure 1.5c). Due to retinal inversion of the eye, if the top pinhole was occluded, the hyperopic eye would no longer see the bottom image and a myopic eye would no longer see the top image.

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Figure 1.5a. In an emmetropic eye, the two narrow pencils of light after passing through the disc are brought to a common single focus on the retina. The subject only sees one image of the light source.

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Figure 1.5b. In hyperopia, the two narrow pencils that pass through the pinhole apertures will focus behind the retina and the subject will again report that there are two images of the source. If the upper pinhole aperture is now blocked by an occluder, the subject will see only upper image.

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Figure 1.5c. In myopia, the two narrow pencils that pass through the pinhole apertures will focus in front of the retina and the subject will again report that there are two images of the source. If the upper pinhole aperture is now blocked by an occluder, the subject will see only lower image

A variation of the Scheiner's multiple pinholes optometer was described by Scheiner (Bennett, 1986), where three pinholes arranged as an equilateral triangle are used instead of the double pinhole (Figure 1.6). Here, ametropia is determined by patients reporting an erect or inverted triangle, with myopic observers reporting the same orientation as the object shown.

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Figure 1.6. An illustration of Scheiner's disc with two, three, and four pinholes (Bennett, 1986).

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Figure 1.7. An illustration of the Scheiner's triple pinhole disc (Bennett, 1986). (a) The shaded area shows the common field of view. (b) An appearance of a single spot looking through a triple pinhole (previous figure). Rays reaching the retina of myopic people are crossed; myopic people see the upright configuration of the trebled spot light because of retinal inversion. (c) In a hyperopic eye, rays reach the retina uncrossed, and the orientation of the pinholes are the same on the retina. The observer sees the triad of dots in an inverted orientation as the pinholes.

Although the concept of multiple pinholes for refractive error measurement is simple, it forms the basis of more modern techniques such as the autorefractor.

1.5.1.1 *Simple optometer*

Ametropia could also be measured by physically locating the far point of the eye. In a myopic eye, this is relatively simple, whereby a fine target is moved away or toward the patient until the object can be seen clearly. The furthest distance for clear vision represents the far point, and could be used to calculate the ametropia. This technique was first described in 1623 by Benito Daza de Valdés where he placed mustard seeds in a line at intervals away from the subject (Bennett, 1986). He would then ask subjects to count seeds and only stop until the seeds became blurry. Again, this gives a measure of the far point, which could be used to calculate the refractive error of simple myopia.

The above method will not work for a hyperopic eye because its far point is located behind the eye. If a positive lens greater than the hyperopic ametropia was placed in front of the hyperopic eye, then the far point would be shifted to be at the front of the eye. A positive lens (usually about 10 D) could be placed at the end of a graduated bar where a test object could be moved freely. The subject would be able to hold this device and adjust the test object whilst looking through the 10 D lens placed at spectacle plane. To measure the ametropia, the test object is usually placed at the remote end of the bar which is in reach of manipulation by the subject. The out of focus test object is slowly moved closer until the test object becomes clear. At this point, if the eye is not accommodating, then the image formed by the lens will be conjugate with the retina (fovea). The disadvantages of this method include proximal accommodation from the subject’s knowledge of the near test object, non-linear bar graduations, and variations in the apparent size of the image as the target approaches the eye.

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Figure 1.8. An illustration of a simple optometer (Anonymous, n. d.). In this illustration, the user would hold the handle of the optometer (D) and would manipulate the test target (B) by holding the knob (E) that is fixed to the target (B). The user would usually position the test target at the far end of the graduated bar (C) and slide the test target (B) closer whilst looking through the eye piece (F) until vision is clear.

1.5.1.2 *Porterfield optometer*

Details are scarce regarding the exact construction, but he did mention the use of a vertical test line as the target, as well as the use of Scheiner’s double-slit. The optometer was probably mainly used to measure the near point of accommodation (Bennett, 1986). Phillipe de la Hire described an improved version of the Porterfield optometer by using a Scheiner pinhole disc together with loose trial lenses. The lens used to acquire an undoubled image of the test object gives a measure of the refractive error (Bennett, 1986).

1.5.1.3 *Young's optometer*

Young's optometer is a simple optometer combined with a Scheiner double-slit aperture (Collom & Levene, 1977). Young engraved a line along the centre of the graduated bar so that subjects would see an 'X' when viewing through the double-slit aperture. The apparent point of intersection of the 'X' would be conjugate with the retina (fovea). Young also suggested the use of a +4.00 D lens (Rabbetts, 2007) or +10.00 D lens (Bennett, 1986) placed in front of the eye to measure hyperopia. He also made suggestions on the tendency for subjects to accommodate and recommended an adjustment of *'two or three degrees lower than that which is thus ascertained'* (Bennett, 1986).

1.5.1.4 *Badal optometer*

The Badal optometer was introduced by Badal in 1876 and uses Newton's relationship whereby the second principal focus of the optometer lens is made to coincide with either the nodal point or the first principal focus of the tested eye (Duke-Elder & Abrams, 1970; Southall, 1918). The advantage of this setup is a constant image angular size regardless of the target location, as well as the uniform power scale (Rosenfield, 2006). If the image is already in focus, then the front nodal point of the eye is the preferred coincident point with the second principal focus of the Badal optometer lens. However, since the Badal optometer is frequently used when the image is defocused, the size of the retinal image is no longer proportional to the image angular size when measured at the nodal point. To minimise error when determining the refractive error, the preferred coincidental point is the entrance pupil of the eye (Smith & Atchison, 1997) or approximately between the entrance pupil and the spectacle plane (Rosenfield, 2006).

1.5.1.5 *Telescopic optometers*

This optometer type has a fixed target position with an adjustable lens position (Cheng & Woo, 2000). Patients would look through the telescope and make adjustments to the eyepiece to clear a distant object, effectively varying the separation of the eyepiece and objective lens. For a Galilean telescope, the effective length of the telescope is shorter for a myopic eye and longer for a hyperopic eye (Rosenfield, 2006).

1.5.1.6 *Chromatic optometer*

The cobalt disc is an example of a chromatic optometer. The test uses the chromatic aberration property of the eye to test for spherical refraction. A cobalt disc is actually a blue glass (cobalt filter) which can absorb the middle region of the visible spectrum. When looking at a small white spot of light through a cobalt disc, this permits the shorter (blue) and longer (red) wavelengths of visible light to enter the eye. The retinal image will then be an overlap of red and blue diffusion circles. In a myopic eye where both red and blue images are focussed anterior to the retina, the red focus would be smaller as it is closer to the retina. The reverse is true in a hyperopic eye, where the blue focus is smaller than the red focus. The spherical lens required to leave the blue and red foci straddling the retina is the endpoint for subjective refraction. To the subject, the blue and red foci would appear to be of similar size.

The duochrome (bichrome) is another type of chromatic optometer. The test also uses the chromatic aberration of the eye to determine ametropia (Davies, 1957). The unaccommodated eye's preferred wavelength of focus at the retina is assumed to be 570 nm (Rabbetts, 2007; Rosenfield, 2006). Light of shorter wavelengths will therefore be focussed in front of the retina, whereas light with longer wavelengths than 570 nm will be focussed behind the retina. A green and red filter conforming to British Standards (BS3668: Green and red Filters used in Ophthalmic Dichromatic and Dissociation Tests) would have peak luminosity at wavelengths near 535 nm and 620 nm, respectively. Assuming the preferred focus of the eye is to yellow light (570 nm), then red light would focus 0.24 D behind the retina, whereas green would focus 0.20 D in front of the retina (Bennett, 1963). An emmetropic eye viewing a duochrome chart would see the black test objects of the red and green backgrounds as being equally clear and of nearly equal brightness to a colour normal observer (Rabbetts, 2007). A myopic eye would form an optical image in front of the retina, and thus, would see black test objects on the red background with better contrast and clarity. On the contrary, an unaccommodated hyperopic eye would form an optical image behind the retina with test objects from the green background having better clarity and contrast.

The duochrome test is, however, unreliable when there are large amounts of ametropia (greater than 1 D), since the test object and background would be grossly out of focus (Davies, 1957). If the test object is too blurry for accurate comparison between the two backgrounds, it is possible to ask patients to compare the test panel itself (Rabbetts, 2007), or, if using a projector chart, to increase the object character size (project chart permitting). The test is also unreliable if the patient has cataracts, whereby the crystalline lens becomes yellow, resulting in a red bias or red preference (Rabbetts, 2007).

1.5.1.7 *Laser refractor*

Coherent lighting reflecting off a diffuse surface will form an interference pattern in the eye. This pattern, known as laser speckle, has a grainy appearance and can be used to measure spherical ametropia (Ingelstam & Ragnarsson, 1972; Knoll, 1966). The speckle will appear to move relative to head movement, and the direction of movement depends on the refractive status of the eye. Appropriate trial lenses placed in front of the eye will neutralise relative movement. The most positive lens to neutralise speckle movement is a measure of the spherical ametropia. This method has good agreement with existing methods (Ronchi & Fontana, 1975).

Laser speckle was combined with the Badal optometer to subjectively measure the spherical refractive error of the eye using near infrared radiation (NIR) (Teel et al., 2008; Teel, Jacobs, Copland, Neal, & Thibos, 2014). Measurements, however, were not made for prescription purposes, but to confirm the assumption that NIR (commonly used in autorefractors and commercial wavefront aberrometer) are reflected deeper in the retina (posterior to the entrance apertures of the cones and near the retinal pigment epithelium)(Kilintari, Pallikaris, Tsiklis, & Ginis, 2010).

White-light speckle optometer was proposed as a possible technique that works on a similar principle to laser speckle (Bahuguna, Singh, & Malacara, 1984). Laser refractors are very useful since the speckle can inhibit accommodation of the eye. However, this test is difficult to administer since each person perceives the speckle differently, and may therefore not understand the test. This is especially true when the ametropia being measured is low.

1.5.1.8 *Virtual reality system*

A team of researchers recently used a 3D virtual reality based system (Figure 1.12) to semi-automate spherical subjective refraction (Pujol et al., 2016). This method has reasonable agreement with the conventional subjective method.

Figure 1.9. a) Prototype to create a virtual environment for spherical subjective refraction (Pujol et al., 2016). b) Right and left oculars for patients to look through. c) Infrared images for eye tracking. d) Simulated view of the right and left micro-displays that the patient sees.

Despite being capable of determining refractive error from scratch, the starting point for refraction is taken from Hartmann-Shack wavefront measurements. It is, therefore, a method of refinement, as full refraction from scratch using this virtual system can be quite elaborate. With this setup, subjects/patients are to look into oculars that may trigger some accommodation — a possible effect that is similar to using microscopes (Richards, 1976), especially in subjects with little experience looking through oculars (Ting, Schmid, Lam, & Edwards, 2006).

1.5.1.9 *Self-refraction (using self-adjustable spectacles)*

Self-refraction was invented by Joshua Silver (a British atomic physicist), and involves the use of a fluid (silicon oil) to fill up two thin membranes to form a lens. The lens is adaptable and has variable power by changing the volume of fluid inside the lens. The user would look at a distant letter chart and could adjust the volume of fluid until the clearest vision is attained. Self-refraction was found to give the user acceptable vision for low levels of simple ametropia (He et al., 2011; Ilechie et al., 2015). Children in a rural area of China appear to tolerate vision through the self-refracted spectacles well (Zhou et al., 2016). Self-refraction was intended to correct ametropia and not take measurements of the actual ametropia itself. Furthermore, once the fluid is sealed off, it is difficult to vary the optical power of the lens. The volume of fluid required for the lens to reach a certain power could be measured and marked along the syringe used to inject the fluid into the membrane, which makes up the lens. With this modification, it is, therefore, possible to measure the spherical ametropia of the eye (±6 D).

Eyejusters, also a form of self-refraction, uses the SlideLens system whereby variable power is achieved by sliding two lenses (that have both positive and negative power profiles) across each other (Eyejusters). This is achieved by rotating small dials located on the frame-front near the inside temple of the frame. The Eyejusters is not meant to measure the level of ametropia, but rather, is designed to aid the user in correcting their ametropia (up to ±4 D). In theory, it is possible to measure ametropia by graduating the amount of overlap to measure combined lens power. However, this has not been done and no peer-reviewed research has been conducted to assess its accuracy.

1.5.1.10 *Focometer*

The focometer uses the Badal optometer's optics to produce a 1x magnification of a real inverted image of a distant target. A Pechan prism system is used internally to rotate the image by 180 °, thus erecting the image (Berger et al., 1993). The user would hold the focometer in one hand and look through it at a distant target. The user would then adjust the focusing mechanism until the clearest image is perceived. The refractive error is read off a linear dioptric scale which varies according to the focusing of the user. The focometer's ability to measure spherical ametropia has an acceptable agreement with existing methods, provided the focometer is used correctly (Berger et al., 1993; du Toit, Soong, Brian, & Ramke, 2006; Smith, Weissberg, & Travison, 2010). Similarly to self-refraction, it may not be suitable for use in a clinical setting, but rather in areas where access to conventional eye care is limited (du Toit et al., 2006).

A limitation with this method is the necessity for the user to follow the correct instructions for good accuracy. The focometer was intended to be used in disadvantaged areas, where accesses to health care and essential amenities (electricity) are limited. It is therefore, not surprising that most users would be untrained observers. For this reason, one researcher recommended repeating measurements multiple times and using only the third measurement because of the steep learning curve that improves with use (du Toit et al., 2006) .

1.5.1.11 *Self-directed online refraction*

Refractive error is calculated based on the user's response to stimuli presented on an electronic screen. An internet connection, a smartphone and computer are necessary to administer the test. In a non-peer reviewed study, the test appeared to agree well with subjective refraction and had high customer satisfaction ("Clinical trial summary report,"). The study assessed the correlation between conventional refraction and online refraction as a way to compare the two methods at measuring refractive error.

A more appropriate test would be to assess the level of agreement between the two methods.

The online test is user-directed and can be done anywhere if the room can be darkened; there is access to a smart phone with an SMS service, a computer and an internet connection. However, there is no guarantee that users understand all of the instructions and the test would proceed assuming instructions have been carried out properly. If instructions were not performed correctly, it is unsure if the result would still be accurate. A vision check is not performed towards the end so it is not possible to check the visual acuity as with conventional refraction. Initial calibration assumes a correct screen size calibration as well as a distance from screen that is determined based on the subject’s shoe size. It is unknown why the developer of the programme would trade a tape measure for a shoe. The developer assumes a consistent shoe sizing across all brands, and that the user is using a shoe size that is correct for the user. Maybe the developer opted for this method of measuring distance out of convenience or to keep the procedure simple. Furthermore, the testing time is approximately 20 minutes, which is only slightly shorter than performing a one-on-one full ocular consultation with a health professional. The test assumes that the user would have good visual acuity which may, or may not, be the case. The range of normal visual acuity ranges from -0.10 to 0.10 logMAR units. The user’s ocular surface and clarity of the crystalline lens may also affect the accuracy of the test. Different screen brightness’ may affect the level of vision, and therefore the responses to the stimuli may differ. Further studies into the above points need to be carried out to assess accuracy and reliability across different display monitors and different users with varying levels of vision. A test on the level of agreement should be performed as well.

Limitations of current methods

1.6

Spherical refractive error measurements currently performed in the clinic by an optometrist and/or ophthalmologist involves the use of a refractor or trial frame with trial lenses.

Although these methods are robust, there are some issues associated with them, including:

- The practitioner must rely on reliable responses of patients to the perceived differences in vision between each lens change.
- If patients are more sensitive and able to perceive the minute differences of the target image with each lens change, the faster and more reliable the refractive error determination. However, the ability to perceive variations in target images with a small dioptric lens change can vary significantly between individuals. Some patients are able to notice 0.125 D changes, while others require changes as high as 1.00 D (Michaels, 1985).
- Other factors that may affect accurate refractive error measurements of the eye, as suggested by Borish & Benjamin (2006) include:
    - Intelligence
    - Past experience
    - Accustomed visual imagery
    - Uncertainty in discriminating small target object differences
    - Poor observers, lack of concentration or fatigue
    - Malingers or intentionally providing misleading responses
    - Health status of the eye and visual system (e.g. cataracts or lens opacity can make test object discrimination more difficult)
    - Systemic health or disease states
    - Testing factors including letter chart, room illumination
    - Physiological pupil size (smaller pupil will increase depth of focus and make result less accurate)
    - Retinal adaptation

    - Target distance, arrangement and composition
    - Time allowed for discrimination between each lens change
    - Type of equipment or the method used
    - Adequate maintenance of equipment (e.g. smudged or dirty refractor lenses will result in unreliable measurements)

To minimise accommodation, test charts are set at 6 metres (20 feet) or further. In Australia, testing rooms of 3 metres or more are often employed. Optometers discussed above can shorten the working space considerably to within arms' reach, but proximal accommodation can be and is often triggered because of the near testing distance.

Projector and electronic charts are commonly used in clinics to test vision and to check for refractive error. They are useful because they offer multiple optotype arrangements and different optotypes (letters, numerals, symbols, pictures etc.). However, these charts are big and bulky to carry, and often require mains power to operate. The charts have good versatility, but poor portability and therefore have limited use in isolated areas (e.g. screening indigenous Australians in remote areas). Printed charts are possible alternatives because they can be carried to any location. However, multiple charts might be needed, and interchanging between large printed charts can be cumbersome.

Most equipment used to measure refractive error will deteriorate with time and requires maintenance to keep them in good working order. Refractor lens often get smudged with fingerprints and requires cleaning. Projector charts will require frequent bulb changes for good chart luminance. Printed letter charts may become dirty or soiled during relocation or with age. Trial frames and trial lenses are probably the only equipment that are both durable, easy to clean and maintain. However, they still require a good letter chart for refractive error measurements.

Using holography as an alternative has many advantages over current methods. Reconstructed images are perceived to be projected at far distances even when the hologram is placed in confined spaces. There is no need for a 6 meter testing distance as is required for subjective refraction using the phoropter. Holograms are also small, compact, and interchangeable. This is an advantage over refraction using printed letter charts. Unlike equipment requiring mains power, holograms can be operated by battery. Furthermore, holography is a good alternative because it does not require frequent maintenance, which is an advantage over projector charts. The laser diode and hologram are both long lasting, and will still operate even if the hologram was to break. Furthermore, holograms are easy to use and quick to perform, with tests only taking about 30 seconds to do.

1.7

Reliability and repeatability of subjective refraction

Many studies have found subjective refraction to have good reliability and repeatability when performed by different practitioners (French & Jennings, 1974; Rosenfield & Chiu, 1995; Smart, 1940) with a theoretical reliability of ± 0.25 D (Blackhurst & Maquire, 1989; Salmon & Horner, 1996). Researchers also found no significant differences between different methods of subjective refraction, such as the bichromatic chart test or the laser speckle optometer (Jennings, 1973; Perrigin, Perrigin, & Grosvenor, 1982; Safir, Hyams, Philpot, & Jagerman, 1970). Based on these studies, if the patient is consistent with their responses, a practitioner should be able to perform subjective refraction to within ± 0.25 D for the spherical component when using the same method and setup. This was confirmed where a researcher estimated the minimum uncertainty of subjective refraction to be ± 0.3 D (Smith, 2006). As expected, inter-practitioner variation was higher with 95% of spherical refraction being within ± 0.50 D and 80% of spherical refraction being within ± 0.25 D (Goss & Grosvenor, 1996).

1.8 Accommodation

1.8.1 Classical approach to accommodation

This theory is useful in clinical practice or when measuring accommodation. It describes the ability of the eye to change its refractive power by varying the curvature of the crystalline lens. In an unaccommodated eye, the ciliary muscle is relaxed whilst the Zonule of Zinn are tensed. This results in the crystalline lens having a flatter curvature. When the eye accommodates, the ciliary muscle is contracted and the zonule of Zinn is relaxed, resulting in the crystalline lens having a steeper curvature (convex shaped). Based on the classical theory of accommodation, the eye is relaxed when there is no accommodation. Classical theory is still useful as it forms the basis for clinical tests (such as amplitude of accommodation measurements).

1.8.2 Modern Theory of Accommodation

Modern theory of accommodation describes that the resting state of the eye assumes an intermediate position from the eye (instead of being zero) (Rabbett, 2007). This theory is also important because it could explain many phenomena that cannot be explained by classical theory. Under certain circumstances, perhaps when the visual stimulus is not enough to control accommodation accurately, there is an involuntary drift of the refractive state towards the resting state (or tonic level). When this happens, the 'inadequate' stimulus causes the individual to temporarily become myopic, and is called 'inadequate-stimulus myopia' (Rabbetts, 2007). Certain stimulus conditions observed by researchers to elicit an involuntary accommodation towards the resting state include night myopia, dark-field myopia, empty-space myopia, instrument myopia and the Mandelbaum effect.

1.8.2.1 *Night myopia*

It was discovered by many astronomers independently that their vision was worst at night time, but the first written account was credited to Nevil Maskelyne in 1789 (Levene, 1965). However, it was Lord Rayleigh's discussion on the subject in 1883 that generated interest in this field (Rabbett, 2007). The level of night myopia varies considerably in the literature, but probably because of the way it is measured and whether it is measured monocularly or binocularly.

One method to measure night myopia was to use a telescope or binocular whilst fixating a distant target. The eye-piece could be adjusted by the subject to obtain the best focus. The difference in the best focus between photopic and scotopic luminance is a measure of the night myopia. Using this method to measure for night myopia on 21 inexperienced observers monocularly, the group had an average night myopia of −0.59 D (ranging from +1.4 D to −3.4 D) (Wald & Griffin, 1947). Measuring night myopia monocularly in 8 experienced observers (by the same researchers) found the night myopia in this group to average −0.31 D (range +1.4 D to −1.9 D). In an independent study on 28 observers using field glasses, night myopia was found to average −2.00 D (range from −0.50 D to −4.00) when measured binocularly (Schober, Dehler, & Kassel, 1970).

The second method to measure night myopia was to measure the threshold illumination for an observer to resolve a course test object as a function of induced ametropia. The observer would look through an adjustable eyepiece (similar to the first method), but instead of varying the focus (as in the first method), the illumination would be adjusted at regular dioptric settings. The lowest luminance setting will occur at a particular dioptric setting, and this setting was assumed to be the optimal focus. This optimal focus compared to the optimal focus under photopic luminance is a measure of the accommodation for night myopia. Using this method, the average night myopia measured on five subjects was found to be −1.4 D (range from −0.75 D to −2.25 D) (Wald & Griffin, 1947). Using a square-wave grating for fixation, the dioptric power of a phoropter lens was used to determine the optimal focus as a function of the various luminance levels. Using this method, the average night myopia was found to be approximately −1.50 D (Koomen, Scolnik, & Tousey, 1951).

1.8.2.2 *Dark-field myopia*

In complete darkness, there is also a tendency for some subjects to relax their accommodation towards the tonic level (Rabbett, 2007). The level of involuntary accommodation could be measured objectively in total darkness using laser speckle in combination with a Badal optometer. This setup (laser speckle optometer) could measure refraction in total darkness, and the difference in refraction under photopic and total darkness conditions is a measure of the dark-field myopia. Measurements done on 120 college students found the average dark-field myopia to be −1.72 D (range from 0 to −4.00 D).

1.8.2.3 *Empty-space myopia*

In the absence of visual stimulus, vision continues to function but accommodation can return to its resting state (tonic level). This can happen during the daytime, such as in foggy conditions or when flying above the clouds where there are little visual details (Rabbett, 2007). Refraction is usually performed in an empty visual field by setting the starting luminance contrast to below threshold and then to gradually increase it. The empty-space refraction is given by the lens power with the lowest luminance contrast setting. The difference between the empty-space refraction and refraction under photopic conditions is the empty-space myopia. Measurements performed on 100 subjects found an average empty-space myopia of −0.75 D, (range from −0.37 D to −1.37 D) (Luckiesh & Moss, 1937). A study by Reece with measurements taken on 25 subjects found a slightly higher mean empty-space myopia of −1.00 D with great variability between subjects (Knoll, 1952). Other researchers found huge intra-subject and inter-subject variability when measuring for empty-space myopia (Westheimer, 1957; Whiteside, 1952, 1957) as well as dark myopia (Westheimer, 1957).

1.8.2.4 *Instrument myopia*

Instrumental myopia is the tendency for some individuals to over-accommodate when using certain instruments, such as microscopes (Rabbett, 2007). A small exit pupil was thought to be the cause for the involuntary accommodation towards the tonic level

(Hennessy, 1975), but other contributory causes included proximal accommodation, image configuration and contrast, magnification and luminance (Schober et al., 1970). Traditionally, instrument myopia was measured on subjects monocularly using microscopes with exit pupils no larger than 2 mm. Similar to other type of 'inadequate stimulus myopia', the instrument myopia measured by researchers had similar mean and spread. The average instrument myopia on 15 young subjects was found to be −1.91 D (range from -0.96 D to -2.78 D) in one study (Hennessy, 1975). A different study found a slightly higher mean instrument myopia of −2.3 D (range of −0.7 D to −4.0 D) (Leibowitz & Owens, 1975). The extensive range for instrument myopia was confirmed in an independent study, but with a higher mean value of −3.0 D (Schober et al., 1970). As already mentioned, a small exit pupil was necessary to induce instrument myopia, and therefore had minimum bearing on the results of this thesis.

1.8.2.5 *The Mandelbaum effect*

The Mandelbaum effect refers to the involuntary accommodation experienced by some individuals when presented with two superimposed but conflicting stimuli (Rabbett, 2007). The degradation to the stimulus is caused from the superimposed stimuli, and the eye tends to focus to the stimulus that is located closer to the dark focus. In other words, if the observer was looking in the distance and an interposed screen was placed at an intermediate distance, then some individuals may respond by accommodation involuntarily towards the tonic level. On the contrary, if the observer was fixating at a near object, and the screen placed at the intermediate distance, then some individuals would reduce their accommodation involuntarily towards the tonic level. The Mandelbaum effect (or accommodation towards the tonic level) was greatest when the screen was placed at the observer's dark focus (Owens, 1979).

1.9 Overview of optical holography

1.9.1 Introduction

The visual effects of a hologram can be quite stunning to a first time observer. In optical holography, the observer looks through a clear glass plate and sees a 3D object that appears to be floating in space. The development of the hologram started when Gabor initially proposed the idea of holographic imaging, although his intended purpose for it was to increase the resolution of electron microscopy (Gabor, 1948, 1949, 1951). The concept was sound and was confirmed by others (El-Sum & Kirkpatrick, 1952; Rogers, 1952), however, Gabor's inline setup for hologram recording resulted in superimposed reconstructed images (twin-images) that degraded image quality (Hariharan, 1984). Due to this reason, holography development was slow until a breakthrough was made to solve the twin-image problem through the use of an off-axis reference beam (Leith & Upatnieks, 1962, 1963). Holographic image quality also dramatically improved with the invention of the laser and research into holography gained momentum. The highly coherent nature of the laser made it possible to record larger diffusely reflecting objects with remarkable depth and parallax (Leith & Upatnieks, 1964). Denisyuk also made a major advancement to the field of holography by recording the hologram with the object and reference beam on opposite sides (Denisyuk, 1962; Denisyuk, 1963, 1965). This resulted in a hologram that could be illuminated with polychromatic illumination from a point source to reconstruct a monochromatic image (Hariharan, 1984).

The scientific applications of optical holography are immense and include:

- High-resolution imaging of aerosols (Thompson, Ward, & Zinky, 1967)
- Imaging through diffused and aberrated media (Kogelnik, 1965; Leith & Upatnieks, 1966)
- Multiple imaging (Groh, 1968; Lu, 1968)
- Computer generated holograms (Lohman & Paris, 1967)
- Production and correction of optical elements (Upatnieks, Vander Lugt, & Leith, 1966)

- Information storage and processing (Stroke, Restrick, Funkhouser, & Brumm, 1965)
- Character recognition (Vander Lugt, Rotz, & Klooster Jr, 1965)
- Holographic interferometry (Brooks, Heflinger, & Wuerker, 1965; Burch, 1965; Collier, Doherty, & Pennington, 1965; Haines & Hildebrand, 1965; Hariharan, 1978; Powell & Stetson, 1965).

Optical holography also paved the way for digital holography and many interesting applications such as Holoscopy (combining digital holograms with optical coherence tomography) for ultrafast lens-less imaging of scattering tissue (Hillmann, Franke, Luhrs, Koch, & Huttmann, 2012; Hillmann, Luhrs, Bonin, Koch, & Huttmann, 2011; Perucho & Mico, 2014), and many other imaging applications (Hayasaki, Liu, & Georges, 2015; Hayasaki, Zhou, Popescu, & Onural, 2014; Kim, Hayasaki, Picart, & Rosen, 2013; Poon, Lee, Yoshikawa, & Osten, 2008).

1.9.2 How holograms work

In holography, both the amplitude and phase of the original wave are recorded. When the entire wave-field is recorded, images produced are 'realistic' and have all 3D features of the original scene, including size, depth, shape, texture and relative position (parallax). This is in contrast to photography, where only the amplitude is recorded resulting in the total loss of 3D and parallax effects.

All detectors of radiation are insensitive to phase, so how is a hologram able to capture phase? This is achieved by converting the phase component of the object into amplitude through the use of a reference wave. Interference from the object and reference waves produces a complex fringe pattern – a sequence of dark and light bands caused from destructive (out-of-phase) and constructive wave interference (in-phase) respectively. Phase variations of the object wave are indirectly recorded because variations between the fringe spacing recorded are dependent on the angle between the two the object and reference beams. Larger differences between the beam angles will result in finer fringes and vice versa.

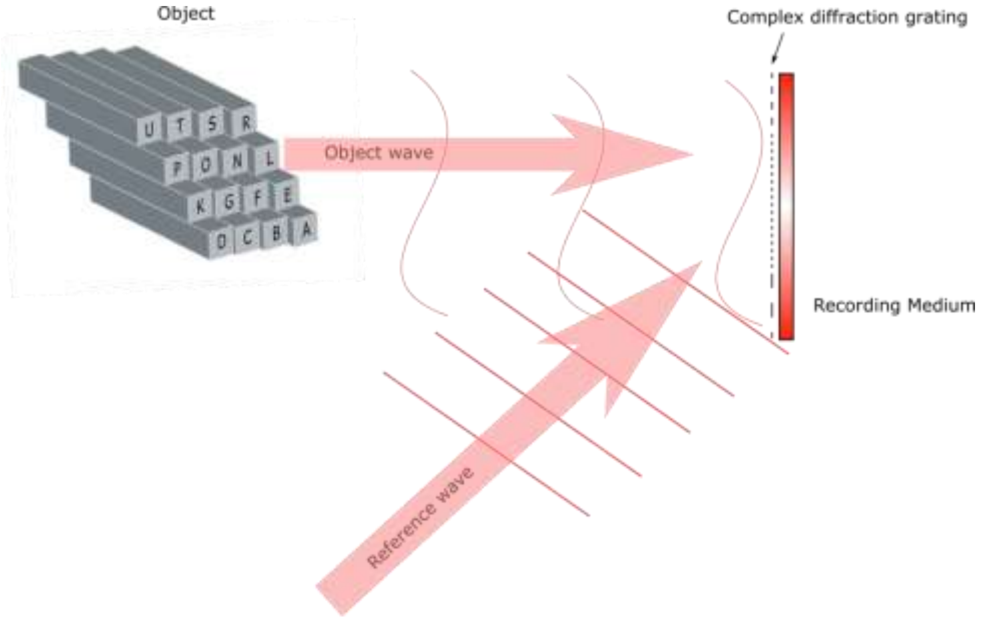

Figure 1.10: Interference from the object and reference waves to form an interference pattern and is recorded onto the recording medium (hologram).

The recording medium (emulsion) contains the object information in the form of diffraction patterns and becomes a hologram after it is developed. To regenerate the original wave, the reference wave is introduced to illuminate the hologram as during recording (Figure 1.10 but without the object wave), resulting in a primary image and a conjugate image. As previously mentioned, the conjugate image was a nuisance back in Gabor’s days of holography because it would interfere with the primary image resulting in a noisy reconstruction. The conjugate image is now no longer an issue because the reference beam could be now introduced obliquely, resulting in two separate images being mirror-symmetrical about the plane of the hologram.

1.9.3 Lasers

Gas lasers are commonly used as the illumination source in holography because they are generally efficient, cheap to acquire, easy to operate, and have good coherence properties. The output wavelength and output power of gas lasers are given in Table 1.2.

Table 1.2. Laser wavelengths and power output

Wavelength (nm)	Laser	Typical Power (mW)	Colour
442	He-Cd	25	violet
458	Ar^+	200	Blue-violet
476	Kr^+	50	blue
477	Ar^+	400	blue
488	Ar^+	1000	Green-blue
514	Ar^+	1400	green
521	Kr^+	70	green
633	He-Ne	2-50	red
647	Kr^+	500	red

The He-Ne laser is commonly used because it is relatively cheaper than other lasers, do not require water cooling and have long working life (Hariharan, 1984). However, the coherence length is relatively short, limiting the size of the object being recorded. The laser shown in the photo (Appendix F5) has been in use for over ten years and is still able to reconstruct holograms with good efficiency.

1.9.4 Types of holograms

1.9.4.1 *Categorising as thin or volume holograms*

When the hologram is recorded on a thin recording medium relative to the average spacing of the interference fringes, the hologram is said to be a thin hologram.
When the recording medium has thicknesses substantially greater than the average fringe spacing, the holograms is classified as being a thick or volume hologram.

Classifying a hologram as thin or volume can sometimes be difficult, but using this formula:

$$Q = \frac{2\pi\lambda_m d}{(n\Lambda)^2} \qquad \text{Equation 1.1}$$

where λ_m is the wavelength in the medium of thickness d and Λ is fringe spacing. A hologram is considered thick if $Q \geq 10$ and thin if $Q \leq 1$. (Bjelkhagen, 2005).
The boundaries between thick and thin holograms are given by the equation

$$P = \frac{\lambda^2}{\Lambda^2 n_0 n_1} \qquad \text{Equation 1.2}$$

with $P < 1$ values for thin holograms $P > 10$ for thick holograms (Nath, 1938). P values between 1 and 10 can be treated as either thin or thick.

1.9.4.2 *Classifying as transmission or reflection holograms*

Transmission holograms are recorded with the reference beam and object of interest on the same side of the recording medium. The hologram reconstruction is usually achieved using a coherent or quasi-coherent light source such as a laser; however, this may not always be the case (such as rainbow holograms). The reference light is 'transmitted' through the hologram towards an observer.

Reflection holograms are recorded with the object beam and reference beam on opposite sides of the recording medium. To reconstruct the hologram, light is 'reflected' off the hologram towards an observer.

1.9.4.3 *Classification as phase or amplitude holograms*

The diffraction pattern that is recorded into the emulsion can be of two types, a refractive index modulation (phase hologram) and/or an absorption modulation (amplitude hologram). As will be discussed in section 1.5.6, phase holograms are more popular because of better image quality.

The hologram used in this thesis is a thin transmission phase hologram

1.9.5 Recording medium

1.9.5.1 *Silver halide photographic emulsions*

This type of recording medium is still the most popular because of the fact that it is readily available as a commercially prepared product and because it has relatively good sensitivity. This was the material that was used to create holograms in the studies comprised in this thesis. The material consists of silver halide crystals being embedded in a gelatin layer. This emulsion is coated on a flexible (film) or stable (glass) substrate material. The silver halide grains can vary in sizes between 10 nm for ultra-fine-grain emulsions to a few microns for highly sensitive emulsions. Silver salts are naturally only sensitive to UV radiation and short wavelengths of the visible spectrum (deep blue, violet). Special sensitisers (dyes) are added to the emulsion to make the material sensitive to commonly used laser wavelengths. Orthochromatic emulsions are sensitive to the green region and panchromatic are sensitive to both red and green regions of light (Bjelkhagen, 2005).

Table 1.3 show some examples of commercially available silver-halide emulsions. PFG-01 is the equivalent to the material used to record holograms in this thesis.

Although the process for the development of this type of recording medium is more cumbersome (needs wet processing and drying), it does offer a stable hologram and the bleaching process actually provides an amplification process to increase diffraction efficiency. Since the optical property of this medium does not change during exposure, another useful property is the ability to record multiple holograms in the one recording emulsion (Hariharan, 1984).

Table 1.3. Examples of commercial available silver halide emulsions

Material	Emulsion Thickness (µm)	Spectral sensitivity (nm)	Grain size (nm)
Slavich			
Red PFG-01	7	<700	35-40
Red PFG-03M	7	<700	10-20
Green VRP-M	7	<550	35-40
Pan PFG-03c	9	400-700	10-20

1.9.5.1.1 Substrates for holographic emulsions

The emulsion needs a strong support during and after the recording for a stable hologram with good quality. A good choice is glass because it is optically clear and mechanically stable. However, glass can be broken when dropped, is slightly heavier, larger and more costly than other alternatives such as film.

Although film is not as stable as glass as a substrate, it is still commonly used as a substrate for mass produced holograms as well as for the production of large-format holograms. Film substrates come in two varieties, a polyester (polyethylene terephthalate) and a cellulose ester (commonly cellulose triacetate or acetate-butyrate)(Bjelkhagen, 2005). Polyester has many advantages over cellulose films, such as higher tensile strength (is mechanically more stable), can be made thinner (and lighter), and has greater resistance to humidity changes. However, polyester is birefringent and may cause problems when recording the hologram.

1.9.5.1.2 Processing of silver halide emulsions

During exposure of the emulsion to light, a latent image is formed which is later developed into a silver image. Processing involves developing, fixing, and bleaching the hologram.

1.9.5.1.2.1 Developing the hologram

A holographic developer consists of developing agent, as well as a preservative (antioxidant), a weak silver-solvent agent, an accelerator (or activator), a restrainer and a solvent (usually water). The type of developer used to develop silver-halide materials will depend on the type of hologram one wishes to create. For amplitude holograms, a high-contrast developer such as the Kodak D-19 is required. For phase holograms, developers based on ascorbic acid, hydroquinone, metol, pyrocatechol, or pyrogallol are often used. The next chapter (Chapter 2) will describe the Kodak D-19 developer, which was used to develop holograms for studies conducted in this thesis. Table 1.4 lists the chemical components to make up the Kodak D-19 developer.

Table 1.4. D-19 developer chemical components and amounts to prepare 1 L and 4 L.

Chemicals	Amounts (kits)	
Distilled water (48C/125F)	500 mL	2500 mL
Metol	2 g	8 g
Sodium sulphite	90 g	360 g
Hydroquinone	8 g	32 g
Sodium carbonate (monohydrate)	52.5 g	210 g
Potassium bromide	5 g	20 g
Cold water to make	1 L	4 L

1.9.5.1.2.2 Procedure to develop the hologram

Dissolve the chemicals in the order listed above by first placing the warm distilled water into a mixing container (can be glass or plastic) and adding a pinch of sodium sulphite. Add the metol and stir the solution to dissolve the solid (the pinch of sodium sulphite was added to prevent the initial oxidation of the metol). Once the metol has completely dissolved, add the remaining sulphite and stir until it dissolves in the solution. Continue by adding the hydroquinone and continue stirring until the solid dissolves. Continue by adding the sodium carbonate and stir until it dissolves as well. Add the potassium bromide and also stir until it dissolves. Finally, add cold water to bring the total volume to the desired amount (1 L or 4 L).

Recommended developing times are based on the temperature of the solution, but can be adjusted by using test strips.

Recommended developing time according to temperature (with agitation)

Temperature	Developing time
16° C / 60° F	12 minutes
18° C / 65° F	10 minutes
20° C / 68° F	9 minutes
21° C/ 70° F	8.5 minutes
24° C/ 75° F	7 minutes

From experience, developing time of approximately 6 minutes appears to work reasonably well in the lab.

According to the author’s knowledge, the Kodak D19 developer is no longer commercially available. However, a substitution for the D19 developer with exactly the same chemical compositions is still currently available.

1.9.5.1.3 Bleaching

After developing the hologram, bleaching is required to convert the developed hologram into a phase hologram. This process raises the diffraction efficiency of the hologram (Blanche, 2013). A phase hologram could be created in two ways, by changing the optical density of the hologram by either manipulating the thicknesses of the emulsion (Altman, 1966; Cathay Jr, 1965) or by manipulating the refractive index (Burckhardt, 1967). The first method can only be used with recording emulsions of relatively low spatial frequencies (Bjelkhagen, 1993), and often result in holograms with poor diffraction efficiencies than the latter method. For this reason, bleaching usually attempts to modulate the refractive index to yield a phase hologram.

There are three methods for bleaching the hologram:

1) Conventional bleaching (or direct re-halogenating bleaching)
2) Fixation-free re-halogenating bleaching
3) Reversal (complementary) or solvent bleaching

The conventional method of bleaching involves converting the developed silver into a transparent silver-halide but only after fixing the hologram (removing the unexposed silver halide crystals). This form of bleaching is not recommended for ultra-fine grain emulsions. As the name suggests, fixation-free bleaching is when the hologram is bleached without undergoing a fixation process. In other words, unexposed silver halide crystals are left intact in the hologram. With the reversal bleaching method, the hologram bypasses the fixation step, and the developed silver is converted to a soluble silver complex that could be dissolved away to leave a phase hologram made up of undeveloped silver halide crystals.

Conventional bleach can produce holograms with good efficiency, but the hologram will have the undesirable effect of scattering light because of the individual grains making up the recording (Benton, 1971) as well as from the non-linear effects during formation of the relief-image, especially at low spatial frequencies (Upatnieks & Leonard, 1970).

A reversal bleach is the preferred method because the phase hologram created will have smaller grains resulting in less scattering (Chang & George, 1970; Hariharan, 1971). This bleaching method was therefore used in the studies comprised in this thesis.
An unwanted effect of the reversal bleaching process is the tendency for the hologram to darken in ambient lighting (because of the printout of the silver) (Hariharan, 1984). Resistance to the printout of the silver could be increased by the formation of suitable silver salt after the developing process. Silver chloride (AgCl) is the least resistant (most susceptible) to this undesirable darkening of the hologram. Silver bromide (AgBr) is a better alternative, but the most resistant salt is silver iodide (AgI). It was recommended by Hariharan to treat the hologram with a solution of potassium iodide (KI) to improve the hologram stability and reduce the darkening of the hologram (Hariharan, Ramanathan, & Kaushik, 1971).

Recommended reversal bleach solution for maximum stability (Hariharan, 1984)

Stock solution A	Amounts
Potassium dichromate	8 g
Sulphuric acid	10 mL
Distilled water	1000 mL
Stock solution B	
Potassium iodide	2 g
Distilled water	1000 mL
Procedure: mix 1 part of stock solution A, 1 part stock solution B and 8 parts distilled water. Bleach for 5 minutes at 20C. Use only once.	

1.9.5.2 *Other practical recording media*

Please refer to Appendix B for other practical recording media

1.9.6 Diffraction efficiencies

The diffraction efficiency of a hologram is defined as the ratio between the intensity of the incident light and the diffracted light (Blanche, 2013). One would desire a hologram with higher efficiency since the reconstructed image will be brighter. Properties of the recording material that will influence the efficiency of a hologram include the thickness, the amplitude of the modulation, the average absorption and the type of modulation recorded (phase, amplitude). In a phase hologram, it is theoretically possible for all incident light to be diffracted, resulting in a theoretically diffraction efficiency of 100% (see table 1.5). On the contrary, amplitude holograms will absorb a portion of the incident light resulting in poorer diffraction efficiency (3.7%). For this reason, amplitude holograms have generally been 'phased' out by phase holograms. Table 1.5 shows the diffraction efficiencies of holograms according to their type.

Table 1.5. Maximum (theoretical) diffraction Efficiencies for different types of holograms (Hariharan, 1984)

Type of Hologram	Modulation	Efficiency (maximum)
thin	Amplitude	0.0625
	Phase	0.339
Volume transmission	Amplitude	0.037
	Refractive index	1.00
Volume reflection	Amplitude	0.072
	Refractive index	1.00

Rationale for research

1.10

Currently, subjective refraction is often confined to a consultation room because equipment such as refractor and projector charts is too bulky to re-locate or usually requires electricity to operate. Other more portable methods, such as refraction using the trial frame and trial lenses still require a letter chart that is also cumbersome to carry around and requires a setup of 6 meters (20 feet) or greater to minimise accommodation.

Holography is a possible alternative because it is capable of capturing the original scene and records it into a thin glass medium that is both portable and can be battery-powered. In this sense, the consultation letter chart setup could be stored in the practitioner's pocket and carried around until needed. The hologram reconstruction will have a letter chart presented at the correct testing distance that will not change or deteriorate with time.

1.11

Research aims

- This thesis aims to determine whether holography could be used to reliably measure the spherical refractive error of the human eye.
- Additionally, this thesis will investigate whether accommodation is inhibited when measured under coherent illumination.

Research hypothesis

1.12

Even in the presence of laser speckle, the quality of the holographic reconstruction of a test chart or object has adequate resolution to permit subjects to discern small differences in character clarity for reliable spherical subjective error measurements.

Our visual system has evolved under incoherent polychromatic illumination. Accommodation of the eye is necessary for tasks such as reading would and function best under this type of illumination. It is hypothesised that the foreign nature of monochromatic coherent illumination would inhibit the accommodative ability of the eye; resulting in the eye under-accommodating to a high contrast near stimulus.

Thesis overview

1.13

Chapter 1 discusses spherical refractive error and evaluates subjective methods to measure it.

Chapter 2 discusses the general method used to record the hologram as well as subject recruitment.

Chapter 3 evaluates the effectiveness of using a holographic logMAR chart for spherical refractive error measurements using trial lenses.

Chapter 4 investigates the inhibition of accommodation when subjects are presented with a hologram of characters located at multiple near vergences. This chapter determines the preferred refractive state of the eye when looking into a hologram with multiple target vergences (MVT).

Chapter 5 investigates the different behaviours of myopic and hyperopic subjects when observing a multi-vergence target hologram.

Chapter 6 discusses a Mandelbaum-like Effect when subjects observe an MVT hologram, but the effect was absent when a holographic logMAR chart was used instead. Vision acuity measurements were also made using this holographic logMAR chart and compared to visual acuity taken with a standard logMAR.

Chapter 7 investigates whether a non-holographic multi-vergence target could also elicit the Mandelbaum-like Effect as observed in the hologram.

Chapter 8 investigates the association between the measured positive blur-limits and myopic progression.

Chapter 9 summarises the research comprised in this thesis and recommendations for future works.

General process for recording holograms

Chapter 2

2.1 The multi-vergence target

Figure 2.1 shows a photo of a multi-vergence target used for hologram recording. This target consists of match sticks glued together with printed labels stuck at one end. These vergences have been originally designed to vary from −1.0 D to +6.5 D in steps of 0.5 D. The test characters seen are arranged in a 4 × 4 array. The dioptric steps between closest targets as well as the vergence ranges can be modified to suit the objective of the experiment.

Fabrication of the MVT was done by gluing match sticks at pre-designated distances while viewing through a travelling microscope. Since sticks are glued manually, there could be some small human error. During recording, the MVT was imaged by a +20 D lens, so these small errors will become more noticeable in terms of deviation from their intended vergences. Nonetheless, actual vergences were measured (refer Appendix F1) and used during calculations to form the result sections that make up the chapters. Although there was a deviation from the intended vergence, actual vergences used in the calculation are a true representation of what subjects can see. Since the results are reliable, the conclusions formed from the results should therefore be valid.

As already mention, a travelling microscope was used to glue the target sticks at specific distances from each other. The microscope had an accuracy of 0.001cm with scales in 0.5mm. There are further 50 vernier scales subdivisions. Therefore, the smallest count is 0.5mm/50 = 0.01mm or 10um. The experimental precision of this microscope is therefore 0.01/2=0.005mm. Assuming the test object being located at 50mm, vergences would have an error of approximately 0.005 D. However, since the consecutive placements of the targets sequentially after each other could compound this experimental error to potentially 0.02 D. To be conservative, this theoretical experimental error was rounded up to 0.10 D (which is still clinical insignificant).

Test characters used are easily printed and could be adapted for the specific experiment. These characters are about 0.75mm in size and are pasted upside-down onto 2mmx2mm matchsticks to form the multi-vergence target Figure 2.1.

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Figure 2.1: Multi-vergence Target with upside down letters pasted at one end.

The multi-vergence target (Figure 2.1) was positioned with the zero vergence target positioned 50 mm from the 20 D lens (Figure 2.2). Rays from the zero vergence target passing through the 20D lens will be seen as having ‘zero’ vergence by the subject. Subsequently, other targets are positioned at the calculated distances from the lens corresponding to their respective target vergences. Table 2.1 shows the intended target vergence, the corresponding refractive error or correction (D), the calculated distance from the lens (mm) and the adjusted distance after correcting for off-axis astigmatism.

Table 2.1: Intended vergence, corresponding refractive error, distance from 20D lens. Adjusted distance is corrected for off-axis astigmatism

Intended Vergence (D)	Corresponding Refractive error (D)	Distance from lens (mm)	Adjusted distance from lens (mm)
4.50	-4.50	-64.52	-63.21
4.00	-4.00	-62.50	-61.45
3.50	-3.50	-60.61	-59.31
3.00	-3.00	-58.82	-56.78
2.50	-2.50	-57.14	-56.62
2.00	-2.00	-55.56	-55.29
1.50	-1.50	-54.05	-53.53
1.00	-1.00	-52.63	-51.34
0.50	-0.50	-51.28	-51.02
0.00	0.00	-50.00	-50.00
-0.50	+0.50	-48.78	-48.52
-1.00	+1.00	-47.62	-46.58
-1.50	+1.50	-46.51	-45.99
-2.00	+2.00	-45.45	-45.19
-2.50	+2.50	-44.44	-43.92
-3.00	+3.00	-43.48	-42.19

The intended vergence is the vergence of the MVT after being image by the +20D lens. This follows the usual sign conventions. However, since the subject places his/her eye on the right side of the hologram (Fig 2.3), the sign convention was reversed to reflect this. So the intended vergence of -2.50 D will in fact be at the far point of a +2.50 D hyperope.

2.2 Setup for recording a hologram

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Figure 2.2. Experimental setup for recording a hologram of a multi-vergence target using a He-Ne laser (not to scale)

Figure 2.2 shows the setup for recording a hologram of a multi-vergence target using a He-Ne laser (A). The beam from the laser is split by a beam-splitter (B) to form a reference beam and an object beam. The object beam is guided by the mirror and is expanded through a 12mm focal length diverging lens (H) to illuminate the object (I) with diffuse laser light. Scattered laser light from the object (I) is gathered by a 20D lens (J) and is directed towards the holographic recording medium (F). The reference beam is ‘cleaned up’ by a spatial filter (C), is collimated by a lens (D) before being directed by a mirror (E) towards the holographic recording medium (F). ‘Cleaning up’ the beam or spatial filtering of the laser beam was done to remove undesirable features of the beam (such as aberrations from dirty, damaged or imperfect optics).

The object and reference beam path lengths were closely matched as possible at the recording plane (F), with the interference from the beams recorded on the holographic recording medium (Agfa 8E75, Slavich PFG-01 or equivalent). The entire setup was placed on an air floating optical table for stability. Agfa 8E75 plates require 50µJ/cm^2 for 50% transmission. Using a low-power He-Ne laser (~1.5 mW), the exposure time required was close to 1hr. The recorded hologram was developed for approximately 6 minutes in Kodak D19 developer and bleached for approximately 4 to 5 minutes in a reversal bleach.

2.3 The Hologram of a multi-vergence target

The hologram of the multi-vergence target is a phase hologram that resembled a transparent glass plate when not illuminated. When illuminated with a plane wave from a He-Ne laser, image wavefronts corresponding to test characters located at various distances from the hologram are generated at the hologram. When this hologram was used to test the vision of a subject, wavefronts having different vergences reach the eye of the subject from the various test characters that are seen through the hologram.

2.4 Hologram reconstruction

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Figure 2.3. Hologram reconstruction

Figure 2.3 shows the arrangement used for hologram reconstruction. It is the same setup for recording, but with some modifications:

- The removal of the object beam path, object and imaging lens.
- Hologram plate flipped or rotated 180° along the vertical axis so that the plane wave illuminating the hologram illuminates the hologram plate from behind (opposite direction to the recording reference wave).

The target and the recording process have been illustrated for three vergences in Figure 2.4.

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Figure 2.4. Recording the hologram of a multi-vergence target. Colours are for illustrative purposes only. Light from the He-Ne laser is red in hue.

The subject's eye was located at the same distance from the hologram plate as the +20 D lens was in the recording arrangement. In such a case, the vergences of the rays reaching the subject's eye from the various characters seen through the hologram will be in the appropriate range as the wavefronts are now phase-conjugated. The sizes of the printed characters are designed such that the angle subtended by the images of the numbers at the eye is a constant 50′. The multi-vergence target was fabricated by hand using a travelling microscope, ‘match-stick like sticks’ and glue. The expected error vergence from the positioning of the sticks was within ±0.10 D. For the intended vergences, the required distance was calculated in mm to 2 decimal places. Placement of these stick targets to this level of accuracy was possible using a travelling microscope. A travelling microscope has scale markings in 0.01 mm steps.

Subjects were directed to read out the characters that they could recognise from negative vergences to positive vergences. The practitioner recorded the characters called out by the subject.

2.5 Object height calculations for zero vergence objects

The logMAR hologram required character sizes that mimic a typical logMAR chart, whereas the MVT hologram all required 50’ angular size at the eye. The object used to record the logMAR and MVT holograms therefore had specific height requirements to achieve the above. While simple linear relationships between object and image rays can be used to calculate the required object height (by knowing the required image parameters), it can be challenging if the image would only focus at optical infinity (plane waves). This is true for all the characters of the logMAR hologram, and the zero vergence of the MVT hologram. To overcome this, angular magnification relationships were used to calculate the required height of the object where images are focussed at infinity. It is well known that the angular magnification of a single lens in an unaccommodated eye is:

$M \sim d/f$ where d = distance of original object from the eye,

f = focal length of lens.

For the zero dioptre object, the object was placed at the focal distance of the lenses ($d = f$), so the angular magnification for this setup is close to 1.

From simple trigonometry calculations, it is then possible to work out the required height of the object.

2.6 Vergence Measurement of the MVT hologram

The setup for the measurement of the holographic target vergences is shown below (Figure 2.5). The setup could be isolated into two main systems, the hologram reconstruction and the focussing system. The setup for the hologram reconstruction is the same as Section 2.4. To focus the hologram for vergence measurement, a condensing lens (Label B) is used to focus the holographic image onto a diffuse screen (Label C). Each individual target needs to be focussed individually by the user, and the measured distance from the condensing lens is used to calculate the target vergence. To aid the user to see the holographic targets and to focus them onto the diffuse screen, a telescope (Label D) is used to magnify the holographic targets. Actual vergences are tabulated in each chapter where appropriate.

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Figure 2.5: Setup for measuring the vergences of the MVT image

It was not possible to directly measure and confirm the size of a holographic target letter. Heights were difficult to measure because of the dim hologram image, small nature of the letters, the fact that the image came from optical infinity and diffraction limitations. The size of holographic objects is usually determined by comparing to another object of known real world size. For example, if a ruler was recorded with the logMAR chart, then it is possible to compare the logMAR letters to this ruler and get an idea of the sizes of the logMAR letters. This was done before recording of the hologram. The logMAR hologram was confirmed to be optically correct through the use of trial lenses and inspection of the chart. If the object heights, object distance and image distance are known, then the image height could be verified. Object heights were measured and confirmed to be correct. This was done using a photo of the logMAR chart along with a ruler and magnifying the photo to aid in verification (Figure Appendix F7). The placement of the logMAR chart (object distance) had to be placed at the focal length of the imaging lens (+2D) for hologram recording. This distance was also verified to be correct by using a telescope set for infinity. This telescope will only see collimated rays, and will only be able to focus the logMAR chart if the chart was placed at the focal length of the +2D imaging lens. Even with a conservative error of 5 mm in chart placement, there would only be a 3 letter error for the zero logMAR line. In practice, the error is lower since rulers are graduated in 1mm scales.

2.7 Using the hologram for testing

The recorded hologram contained the images of various characters located at different distances from the lens. These images were recreated at different distances from the hologram when the hologram was illuminated appropriately. Figure 2.6 illustrates the illumination and reconstruction of the images from the hologram when it is used in the experiment.

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Figure 2.6. Using the hologram to test vision.

It is well known that when the hologram is illuminated by the plane reference wave that was used while recording, the image-forming wavefronts are regenerated. However, if the hologram is illuminated from behind by a plane reference wave travelling in the opposite direction, the phase-conjugate of the recorded image-forming wavefronts are regenerated and the direction of propagation of each ray of the image forming wavefront is reversed. In testing vision using this hologram, the subject is made to place his or her eye at the same location relative to the hologram as was the imaging lens during the recording process. The hologram is illuminated from behind by the reverse travelling reference wave. When the hologram is thus illuminated, the subject viewing through the hologram will receive the phase-conjugated waves of the recorded wavefronts and see the images of various characters at different locations from the eye. The angular size of the images seen through the hologram is 50′, which corresponds to the angular size of ‘60-metre’ letters at 6 m distance.

When not illuminated, the hologram of an MVT resembles clear glass. With one eye occluded, the subject’s un-occluded eye was corrected and then directed to look through the un-illuminated and clear hologram plate at a 1.30 logMAR (20/400)-size letter ‘E’ located 6 m (20 feet) from the subject. When the hologram plate was illuminated with the same recording He-Ne laser (633 nm), a holographic reconstruction of the MVT with high-contrast characters appeared in front of the subject. The reconstructed four-by-four array of characters appeared to be floating in free space and was red in appearance. Holographic characters located near the far point of the subject eye will form optical images in proximity to the retina. Some optical images formed close to the eye will be recognisable to the subject, whilst others formed further away will be too blurry for character recognition.

Subjects are instructed that when they view through the hologram they will see an array of characters, some of which will be clear and some blurred. They are advised to read out the character that they can recognise from the top row to the bottom row, going from left to right. Unless told otherwise, subjects are usually distance corrected using the spherical equivalent from the subjective refraction performed during the screening process.

Measuring the positive blur limit (PBL)

2.8 To test the PBL, the practitioner removes the laser block to permit laser light to reach the hologram plate. The subject sees a multi-vergence hologram which appears to float before them. Instructions are repeated to the subject, and the practitioner notes the response.

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Figure 2.7: Schematic diagram of the arrangement used to test subjects with the hologram. The Eyecup is to ensure the correct eye position from the hologram. The eye-cup also has a provision to insert a trial lens for the subject’s best vision sphere.

Please see Figure 2.8 for a simulation of the view that is obtained by a spectacle corrected subject seeing through the hologram. This view was obtained using a camera focused to infinity. This particular hologram uses integers with the numeral ‘0’ that is seen in sharp focus and corresponds to zero vergence. Numerals ‘–1’ and ‘–2’ corresponded to negative vergences, the numbers ‘+1’, ‘+2’ and the rest correspond to positive vergences. Viewing through the hologram, the distance (spectacle) corrected subject will see characters having negative vergences (‘–1’ and ‘–2’) clearly by exercising his/her accommodation. The character having zero vergences (‘0’) will be seen clearly by the subject without using accommodation. Positive vergence at the eye implies positive blur. An uncorrected and relaxed (unaccommodating) hyperope will see some characters with positive vergences depending on the level of hyperopia and the depth of focus of the eye. The simulated view of such a subject viewing through the hologram is shown in Figure 2.9. This view is obtained using a camera focused to infinity with a −2 D lens placed in front of it to simulate hyperopia.

Characters having positive vergences will be seen blurred by all *spectacle corrected subjects* as the eye cannot exercise negative accommodation. The range of positive vergence characters recognised by the subject is limited by the amount of positive blur at the eye tolerated by the subject. The character with most positive vergence that is recognised by a spectacle corrected subject gives a measure of the PBL of the subject for the recognition of the 50’ size characters viewed through the hologram. PBL was defined as the maximum positive vergence (blur) tolerated by the subject before character recognition becomes incorrect. Guessing was permitted and was encouraged. During the experiment, there were occasions where subjects made a mistake and misread a character. This mistake was obvious because a character with low positive blur was read incorrectly follow by correctly reading subsequent ‘harder’ characters. In this case, the mistake was ignored if one or more subsequent characters were correctly recognised (after the mistake was made). When two consecutive errors were made by the subject, then the last correctly called character was used as the PBL endpoint.

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Figure 2.8 Simulation of a spectacle-corrected subject's view through the hologram, obtained using the camera focused to infinity. Here, numerals are used as the test target.

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Figure 2.9 Simulation of an uncorrected and relaxed hyperopic view through the hologram, obtained with a -2 D lens placed in front of the camera focused to infinity.

As the test characters seen through the hologram are very large and the speckle size is very fine, coherent noise due to speckle was not an issue in the experiment. This can be seen in the simulation photographs shown above.

2.9 Subject screening: subjective refraction and preliminary testings

Unless specifically stated, the inclusion criteria for all experiments included:

- Good visual acuity (6/6 or better)
- low astigmatism (0.50 DC or less)
- no ocular pathologies (such as cataracts, pterygium etc.)
- When both eyes were suitable for inclusion, only one eye was randomly selected (unless otherwise stated).

Exclusion criteria included:

- Cannot give informed consent
- Poor visual acuity
- High astigmatism
- ocular pathology (such as cataracts, pterygium, keratoconus, etc.)
- rigid contact lens wearer (including users of ortho-keratology)

Unless stated otherwise, a standard conventional subjective refraction was performed using a refractor head (Rodenstock Phorovist200) and a projector chart (Rodenstock Rodavist 247, with new bulbs, NARVA 12V 20W) set for 6 metres (20 feet) testing distance through the use of a mirror.

A ±0.25 D Jackson cross-cylinder was used to measure astigmatism subjectively.
Slit-lamp, slit-lamp fundoscopy (or ophthalmoscopy) and visual acuity measurements were performed to ensure good ocular health and vision.

Objective refraction

2.10

Spherical refractive error measurements made with the hologram was compared to conventional refraction as well as objective methods (autorefraction). Also, objective refraction was used to identify spurious subjective data that could have arisen from poor communication or incomprehension of instructions, and subject fatigue (to name a few).

For my original experiment (see Appendix A), BOC Instruments http://www.bocinstruments.com.au/) loaned me the Nidek ARK-730A which has auto-track and auto-shot capabilities. A gross alignment and a reminder for the subject to relax and “look at the distant object” is all that is necessary for measurements to be taken. Any practitioner bias is minimised. However, this auto-refractor required subjects to look into a small and confined space, so it was difficult to compare the results from holographic refraction where the procedure is open-field with subjects looking into open space. Furthermore, there were no known peer-reviewed publications to determine the validity of this auto-refraction at measuring the refractive error of the human eye. The Grand Seiko WAM-5500 (Grand Seiko Co. Ltd., Hiroshima, Japan, http://www.grandseiko.com/english/WAM-5500e.htm) replaced the Nidek auto-refractor for the purpose of determining the validity of using a hologram for spherical subjective refraction (Chapter 3). The Grand Seiko WAM-5500 is an open-field binocular auto-refractor that has good agreement with subjective methods (Sheppard & Davies, 2010; Win-Hall, Houser, & Glasser, 2010). Apart from the advantages of being quick to take measurement and is open-field, the auto-refractor also takes pupil measurements simultaneously in the tested eye.

Pupil size measurements

2.11

Pupil measurement is an important consideration for any optical system, and the eye is included. The smaller pupil size generally reduces the blur circle diameter at the eye, resulting in less blur being perceived and as a result, better vision. To determine whether pupil size has any influence on the results observed, pupil sizes were measured using three different methods (that had greater sophistication) as the candidature progressed. Equivalence testing for the different methods of pupil measurement was not necessary because only one method of pupil measurement was used for each chapter/study (except for Chapter 7). In Chapter 7, this study had two distinct experiments, and two different methods for pupil size measurements were used for each experiment. However, separate data analyses (see section 7.3.1 and section 7.3.2) were performed for each experiment. That is, the author did not pool the pupil measurements together for analysis. For this reason, a test for equivalence was not necessary.

2.11.1 Pupil gauge

Using a pupil gauge was a rudimentary method of assessing pupil size. Nonetheless, it served its purpose until a more sophisticated and accurate method could replace it. Under the same illumination as during testings, a pupil gauge was placed near the eye and subjects were asked to look straight ahead. One practitioner then took measurements.

Sample size calculations

2.12

One of the specific aims of the thesis was to measure the IA between myopic and hyperopic subjects. In a previous pilot study using a numerical MVT hologram, it was discovered that the difference between the two refractive groups was about 0.75 D with a standard deviation of about 0.50 D (Nguyen, 2012). In this study, it was discovered that some myopic subjects were behaving differently by exhibiting an IA in the hologram.

The sample size was calculated using the PS Power and Sample Size Calculations (Dupont & Plummer, 2009, 1990). To investigate the difference in PBL between myopic and hyperopic subjects, a continuous response from the independent control group and the experimental subject group was planned with the goal of one control (hyperopic subject) per experimental subject (myopic subject). In a previous study the PBL (dependent variable) within each subject group was normally distributed with standard deviation 0.5 D (Nguyen, 2012). If the true difference between the refractive groups had a mean of 0.75 D (Nguyen, 2012), then at least 10 myopic and 10 hyperopic subjects will need to be recruited to be able to reject the null hypothesis. The power required for this was 0.9. The Type I error associated with this test of the null hypothesis was 0.05.

The emmetropic group was intentionally left out of the study in Chapter 7 because it was discovered, from the pilot study, that the emmetropic subjects were behaving erratically. Furthermore, classification of the refractive group was based on subjective refraction, which was found to have relatively low intra and inter-practitioner repeatability of approximately ±0.50 D (Goss & Grosvenor, 1996). By removing the emmetropic group from the analysis, it was possible to avoid the problem of wrongly classifying subjects with low ametropia into the wrong refractive group.

Generally, more subjects were recruited than anticipated because of the difficulty in recruiting young hyperopic subjects. A lot of the subjects who volunteered into the study were university students and these students had varying degree of myopia. Subject recruitment continued until a sufficient number of hyperopic subjects were recruited (according to the sample size calculations).

Chapter 3

Hybrid holographic refraction: refining subjective refraction using a logMAR hologram and trial lenses

This chapter has been accepted for publication and is in press as follows:

Nguyen, N. H. N. (in press). Holographic Refraction and the Measurement of Spherical Ametropia. *Optom Vis Sci*.

3.1 Introduction

Subjective refraction is part of an optometrist's daily routine to elicit and correct the refractive error of patients. Refraction is often carried out in the clinic using test charts at 4 m or 6 m distance. Often in small rooms practitioners use mirrors to extend the distance at which the chart is presented. Room illumination, chart luminance, testing distance and letter arrangements, and chart layout will, therefore, vary between clinics and locations. Projector charts with multiple letter configurations are still in mainstream use, but letter contrast may differ between visits as the projector bulb or lens may attract dust and dirt, reducing the contrast over time.

The use of a holographic logMAR chart is unique because it could provide a chart at optical infinity with uniform test distance and constant illumination under one system. Furthermore, letter contrast is not degraded through wear and tear and repeated use. Recently, a holographic logMAR chart at infinity was used to test the vision of various spectacle corrected subjects (Nguyen, Avudainayagam, & Avudainayagam, 2013). In the current chapter, the possibility of performing spherical refraction using such a target in a hologram (holographic refraction) was explored. This chapter also compared holographic refraction to auto-refraction and subjective refraction using a standard logMAR chart at 6 m distance under polychromatic illumination (conventional refraction).

The research aim was to investigate the accuracy of the holographic MVT at measuring the spherical refractive error of the human eye. It was hypothesis that subjects can appreciate the difference in character vergences of the reconstructed holographic MVT image to permit accurate spherical refractive error measurement.

3.2 Methods

3.2.1 Subject recruitment:

Please refer to section 2.9 for the inclusion and exclusion criteria.

The research adhered to the Tenets of the Declaration of Helsinki and informed consent was attained for each subject. Ethics approval was granted by the University of New South Wales Australia Human Research Ethics Advisory Panel. See Appendix C for participant's information statement and consent forms.

3.2.2 Autorefractor

An open field autorefractor (Grand Seiko WAM-5500) was used to objectively determine the refractive error. With one eye occluded, the subject's un-occluded eye would look through the clear window of the autorefractor at a 6/120 (20/400) size high contrast character located 6 m away. The autorefractor was set to measure in 0.01 D steps at a vertex distance of 12 mm. Measurement using the calibration tool revealed a small positive bias of 0.02 D. Pupil size in 0.1 mm steps was also measured simultaneously by the autorefractor. The median of five or more autorefraction readings was taken, and the spherical equivalent was used to represent the objective spherical refractive error of the subject. More than five readings would be taken if one of the readings was observed to be invalid. This could be from the subject blinking or exhibiting erratic eye movements or turns.

The average of five or more pupil measurements was used to assess the pupil size for the subject. Since room illumination was kept constantly dim (mesopic conditions), this pupil measurement was assumed not to vary significantly throughout the experiment. Since pupil sizes were presumed to remain similar throughout the experiment, the level of visual acuities would remain the similar throughout the different refractive techniques.

3.2.3 Subjective refraction using a logMAR chart set at 6 metres under white light

Subjects were seated behind a refractor and asked to view a high contrast logMAR chart located 6 m away. The spherical equivalent from a standard full spherocylindrical subjective refraction (see section 2.9) with the addition of a +0.50 D fogging lens (S_{fog}) was used as the starting point for spherical subjective refraction. A minus lens was introduced until best visual acuity was attained. In cases where improvement to vision was minimal (i.e., only one letter gain), the minus lens was disregarded for all subjects irrespective of their ametropia. If two letters were read correctly, then the lens would be accepted (whether from the same line or next line down). This was done to minimise the chance of over-minusing the subject. Subjects were permitted to guess. This endpoint was cross-checked with a duochrome chart, with the expectation of equal clarity between the 'red' and 'green' for all subjects. The expectation was realised for most subjects, however, refraction started with optical fog, and because of the depth of focus, a slight red preference was also expected for some subjects. This endpoint (red bias) was also accepted. The spherical lens corresponding to the endpoint thus obtained was recorded as the conventional refraction reading.

3.2.4 The hologram of a logMAR chart

Figure 3.1 shows the experimental arrangement to record the logMAR hologram. A logMAR chart used for testing vision at 50 cm distance was placed at the primary focal plane of a lens of focal length 50 cm and illuminated by a diverging beam of laser light from a 633 nm He-Ne laser.

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Figure 3.1. Representation of the experimental setup to record a holographic logMAR chart at optical infinity.

The image of the chart is formed at infinity by this lens and appears red in hue. The image forming wavefront emerging from the lens is recorded onto a holographic plate by interference with a plane reference wave derived from the same laser. The holographic plate is then processed to yield a phase hologram of the logMAR chart which resembles a transparent glass plate.

Figure 3.2 shows the experimental arrangement for reconstruction of the logMAR hologram. A subject viewing through this hologram suitably illuminated by a plane reference wave from a 633 nm He-Ne laser would see the phase conjugated wavefront consisting of high contrast letters of the logMAR chart. These letters are at infinity and are of angular sizes corresponding to visual acuities in the range of- 0.1 logMAR to 1.1 logMAR.

A subject viewing through this hologram suitably illuminated by a plane reference wave from a 633 nm He-Ne laser would see a phase conjugated wavefront. The phase conjugated wavefront would, in turn, reveal high contrast non-serif letters (of similar legibility) of the logMAR chart at infinity with angular sizes corresponding to visual acuities in the range of -0.1 logMAR to 1.1 logMAR.'

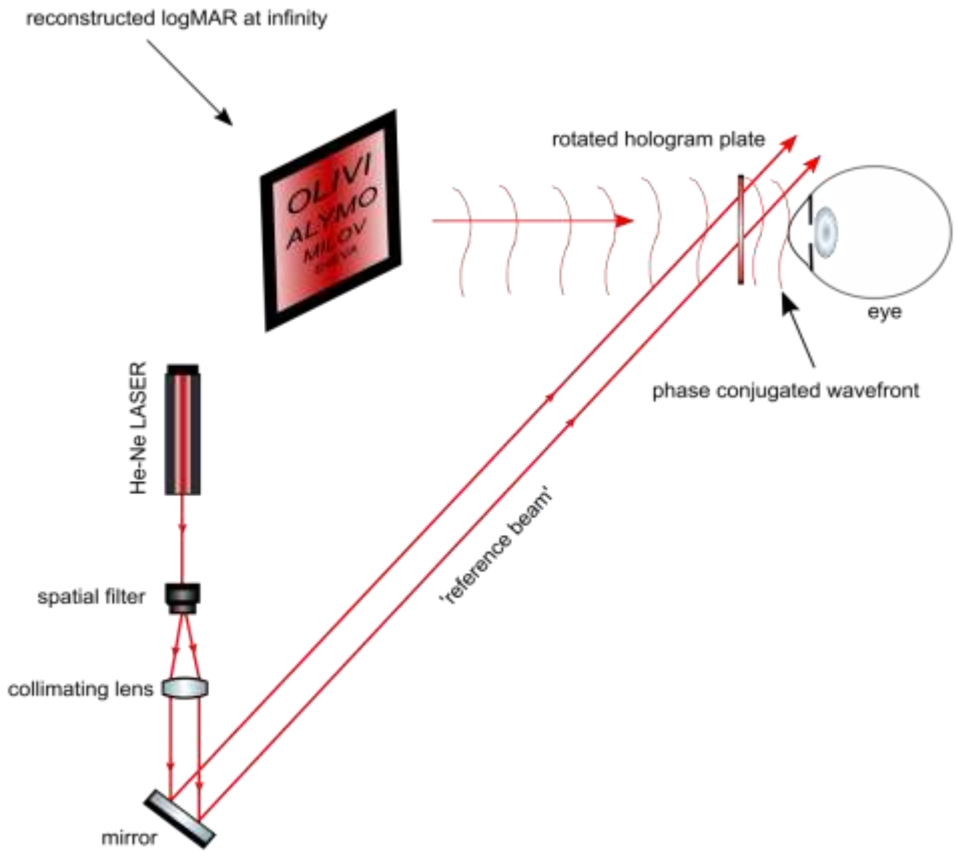


Figure 3.2 An eye looking through the hologram illuminated by the reference beam at the appropriate angle will see the phase conjugated wavefront of a 'reconstructed' high contrast logMAR chart at true infinity.

3.2.5 Subjective refraction using a logMAR chart at infinity recorded in a hologram

With one eye occluded, the subject's un-occluded eye was directed to look through the unilluminated and clear hologram plate at a 6/120 size E at 6 m. The reference beam was subsequently unblocked to reveal the holographic logMAR chart with high contrast characters already described above. S_{fog} was used as the starting lens for holographic refraction. Minus trial lenses in -0.25 D steps were introduced at the spectacle plane via a trial lens holder until 'best' visual acuity was attained. In cases where improvement to vision was minimal with an added lens (e.g., only one letter gain), the lens was disregarded. The spherical endpoint using the holographic logMAR chart was recorded. Autorefraction, conventional refraction, and holographic refraction were all performed sequentially (in that order) in one session by one sole practitioner under the same room conditions. Both conventional and hologram charts had fixed letters but these charts were different to each other to prevent chart learning and memorisation effects during measurements. Actual conventional spherical refraction and holographic spherical refraction each took a minute to perform. To reduce the effects of subject fatigue, subjects were given a few minutes to recover between methods.

3.2.6 Statistical consideration

The methods of Bland and Altman(Bland & Altman, 1986) were used to compare the level of agreement between conventional refraction and autorefraction (both standard methods) with holographic refraction (the new method). The level of agreement was indicated by the mean difference (MD) between the paired measurements (standard and new) and the agreement limits interval of this mean difference (95% agreement limit = MD ± 1.96 × SD).

Paired t-tests were undertaken to compare the means between conventional refraction, holographic refraction and autorefraction, with the null hypothesis of there being no difference between means.
Statistical significance was set at 0.05.

3.3

Results

Twenty-three subjects were recruited with ages ranging from 8 to 63 years old. Table 3.1 and Table 3.2 show the raw refractive data and summary statistics.

Table 3.1 Descriptive statistics with mean spheres (D) for autorefraction, conventional refraction and holographic refraction.

Subject reference	Autorefractor (D)	Conventional refraction (D)	Holographic refraction (D)	Age (years)	Pupil size (mm)
1	-5.55	-5.50	-5.50	17	7.8
2	-4.61	-4.75	-4.75	17	8.5
3	-2.17	-3.00	-3.00	18	7.2
4	-2.17	-2.75	-3.00	18	7.2
5	-2.65	-2.50	-3.00	18	8.5
6	-1.69	-1.75	-1.75	20	6.4
7	-1.93	-1.75	-2.00	10	6.0
8	-1.48	-1.25	-1.50	8	7.1
9	0.18	-0.75	-0.75	52	6.3
10	-0.63	-0.75	-1.00	43	7.1
11	-0.37	-0.75	-1.25	12	6.7
12	-1.14	-0.50	-0.50	55	5.5
13	0.18	-0.50	-0.50	56	7.1
14	-0.03	0.00	0.00	39	5.4
15	0.40	0.00	0.00	20	7.0
16	0.58	0.00	0.00	47	5.1
17	0.99	0.25	0.25	47	5.2
18	0.29	0.25	0.00	19	6.9
19	0.87	0.25	0.00	40	6.9
20	1.40	0.75	0.75	48	6.1
21	1.50	1.50	1.50	58	5.8
22	2.33	1.75	1.75	63	6.1
23	2.28	2.00	2.00	55	4.0
Mean	-0.58	-0.86	-0.97	34	6.5
SD	2.01	1.89	1.92	18	1.1

Table 3.2 Comparison between different types of refractions

n = 23	Difference between refraction methods		
	Autorefractor – Conventional	Autorefractor – Holographic	Holographic - Conventional
Mean (D)	0.27	0.38	-0.11
SD (D)	0.40	0.40	0.17
Significance (*p*)	.003	<.001	.005
Within ±0.50 (%)	57	52	74
Within ±0.75 (%)	87	78	100
Within ±1.00 (%)	100	100	100

Spherical refraction obtained by holographic refraction was plotted against the measurements obtained by conventional refraction (Figure 3.3).

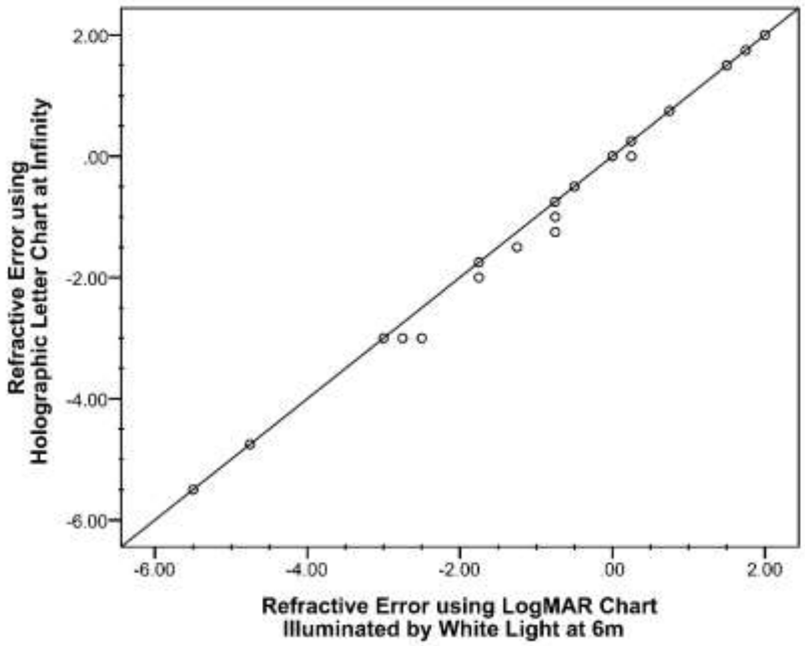


Figure 3.3 Plot of measurements obtained with holographic refraction using the logMAR chart at infinity in a hologram vs conventional refraction using logMAR chart at 6 m in white light as a target. The line of equality has also been plotted.

Of the 23 subjects that were measured, measurements for 15 lie on the line of equality. So for 65% of the subjects the measured values were the same by both methods. When it was different, the holographic method always gave a slightly more negative value. This was the case for the remaining 8 subjects, i.e. for 35% of the measurements.

A scatter diagram of the difference between holographic and conventional subjective refraction was plotted against the average of the two methods (Figure 3.4).

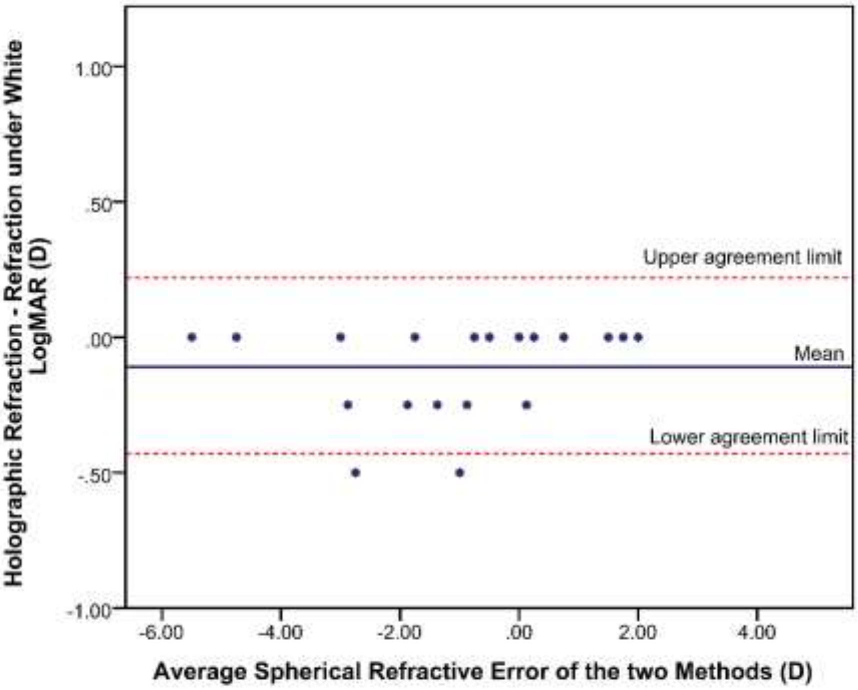


Figure 3.4 Difference between subjective refraction under white light and holographic refraction by an optometrist, plotted against the mean refractive error. Mean bias is indicated by solid line (blue) and the broken line (red) indicates the 95% limits of agreement.

The mean difference between the two methods was -0.11 D (SD = 0.17 D, *P = 0.*005), with the holographic method giving a more negative value. The 95% limits of agreement were calculated using the mean ± 1.96 SD and were also plotted. The distribution of the data showed a consistent systematic bias.

Holographic refraction was plotted against auto-refraction along with the line of equality (Figure 3.5).

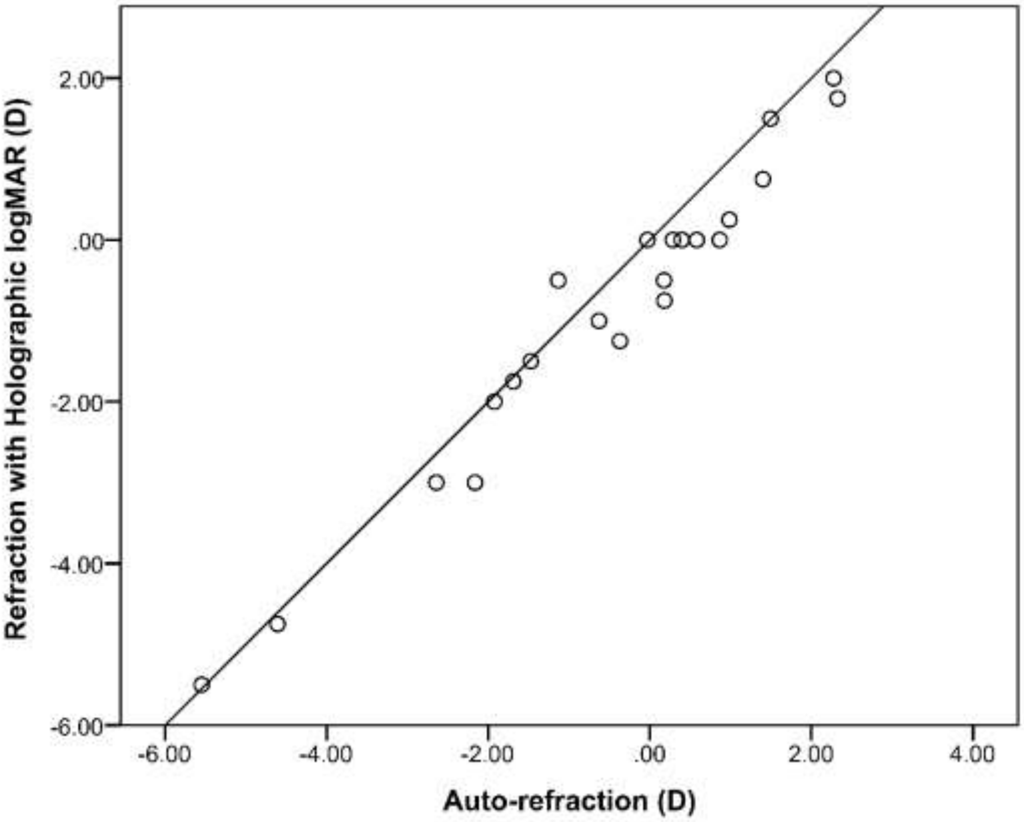


Figure 3.5 Plot of measurements obtained with the holographic logMAR chart at infinity vs conventional logMAR. Also plotted is the line of equality.

The majority of spherical equivalent autorefractor readings were equal to or more positive than the holographic refraction measurements. Figure 3.6 shows the average difference between these two methods with holographic refraction measuring more negatively indicating a more myopic/less hyperopic endpoint. Again, a relatively uniform distribution of data (Figure 3.6) showed an absolute systematic bias.

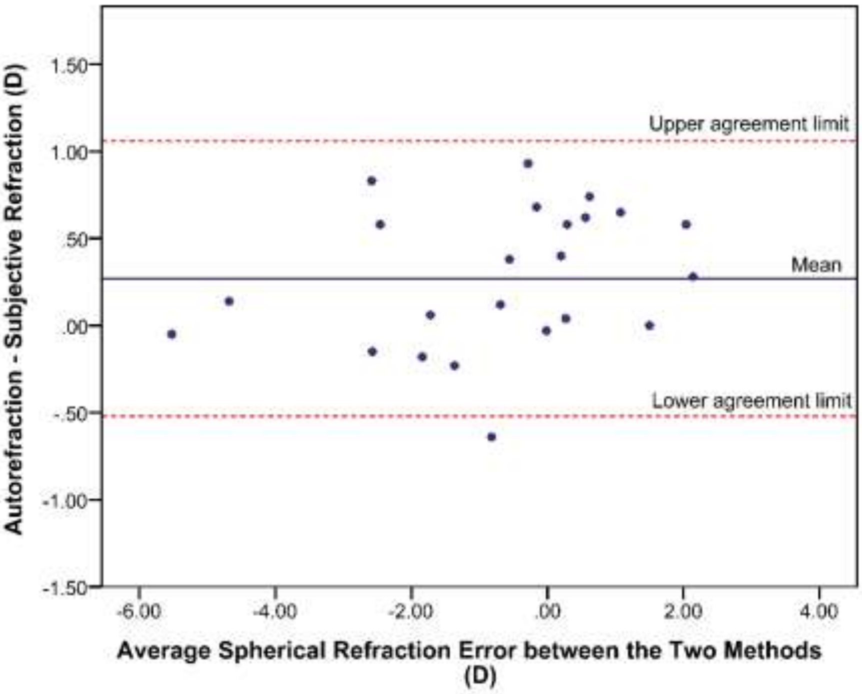


Figure 3.6 Difference between autorefraction and holographic refraction by an optometrist, plotted against the mean refractive error. Mean bias is indicated by solid line (blue) and the 95% limits of agreement are indicated by the broken lines (red).

An analysis between conventional and autorefractor was also performed. Spherical refraction obtained by conventional subjective refraction was plotted against the measurements obtained by autorefractor (Figure 3.7) along with the line of equality.

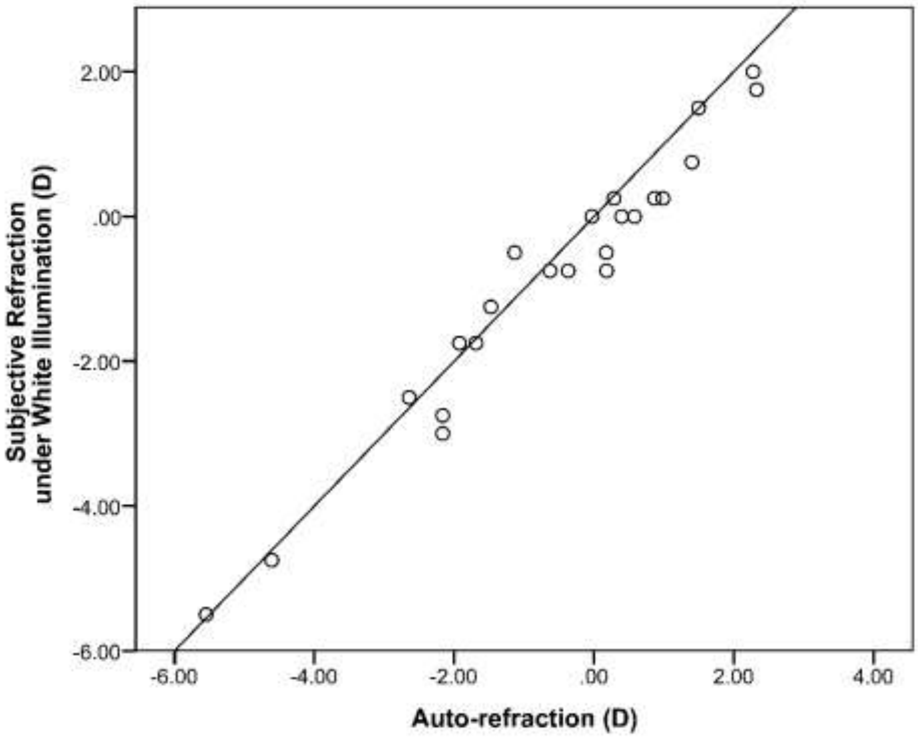


Figure 3.7. The plot of spherical refractive error measured from autorefractor and conventional refraction. The line of equality has also been plotted.

More data points were located under the line of equality, suggesting a more positive autorefractor reading. A scatter diagram of the difference between conventional subjective refraction and autorefraction was plotted against the average of the two methods (Figure 3.8).

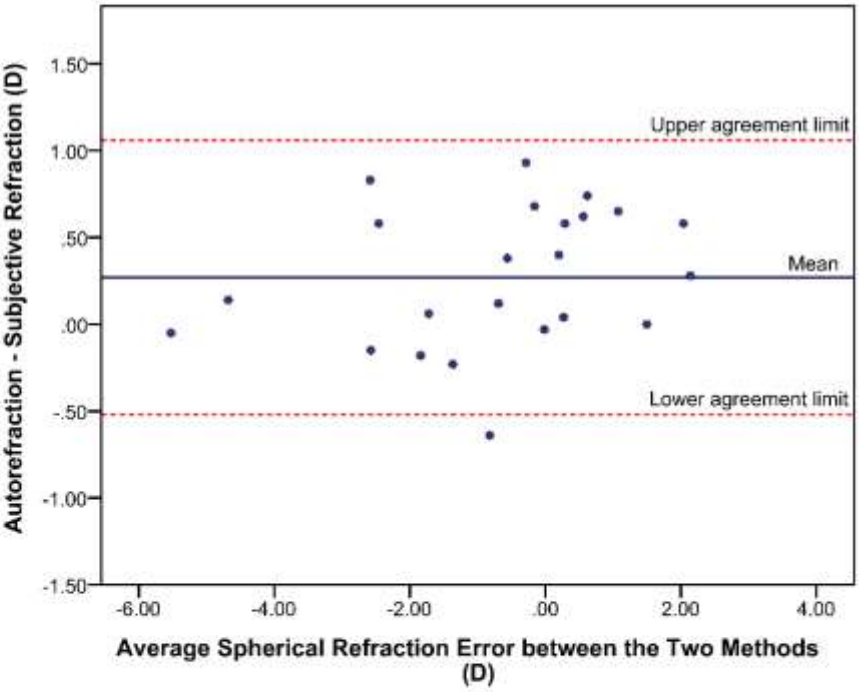


Figure 3.8. The difference between autorefractor and subjective refraction by an optometrist plotted against the mean refractive error. Mean bias is indicated by solid line (blue) and the 95% limits of agreement are indicated by the broken lines (red).

The mean difference between the two methods was +0.27 D (SD = 0.40 D, *P = 0.*03) with the subjective method being more negative.

3.4 Discussion

3.4.1 Holographic refraction compared to conventional refraction

Spherical refractive error obtained using a logMAR chart at infinity in a hologram was similar to that obtained using a standard logMAR chart at 6 m distance in white light. For 15 out of the 23 cases, the spherical equivalent corrections obtained by both methods were exactly the same.

In a review of conventional refraction, most studies reported an intra and inter-practitioner 95% agreement of ± 0.50 D for spherical equivalent, sphere power, and cylindrical power. (Goss & Grosvenor, 1996) The 95% agreement between subjective refraction and holographic refraction was ± 0.34 D and agreement which was better than that for repeated subjective refraction. This suggests that it is possible to use the two methods interchangeably.

3.4.2 Holographic refraction compared to autorefractor

The LoA between the WAM 5500 autorefractor measurements and standard clinical refraction were found by Sheppard and Davies to be -0.01 D ± 0.75 D. (Sheppard & Davies, 2010) The LoA between the same autorefractor model and holographic refraction in this study was +0.38 D ± 0.77 D. The LoA between autorefraction and conventional refraction was +0.27 D ± 0.79 D. This suggested that autorefraction was not a good replacement for subjective methods.
The 95% intervals of agreement were similar suggesting that after correcting for systematic bias, the performance of holographic refraction was similar to conventional refraction when compared to autorefraction.

Sheppard and Davies reported a mean difference of -0.01 D, whereas the present study found autorefraction to be biased by +0.38 D over conventional refraction. The difference could be due to their experimental design, which involved encouraging subjects with vision equal to 6/12 or better to resolve the smallest characters possible without correction. Young hyperopic subjects (mean age = 25 ± 9 years) were therefore encouraged to accommodate, and this could have resulted in a more negative objective refraction.

3.4.3 Adjusting for object vergence differences between holographic and conventional subjective refraction

Comparing the clinical performance of the holographic refraction and conventional refraction revealed very close agreement with clinically insignificant mean differences. However, conventional subjective refraction was performed with the letter chart being located at six metres and therefore had an object vergence of 0.17 D. Wavefronts from the holographic logMAR chart arrived from optical infinity and had an object vergence of 0.0 D. A negative correction of 0.17 D should be applied to conventional refraction to correct for this vergence difference.

Correction for the difference in chart vergence changed the mean difference between the two methods from 0.11 D ($P = 0.005$) to 0.06 D ($t(22) = 1.679$, $P = 0.11$, paired t-test). Although the agreement limits were unchanged, the average difference between holographic and conventional spherical refractions became smaller and the P-value changed from statistically significant to being non-significant. This provides greater confidence for the two techniques to be used interchangeably.

3.4.4 Effect of chromatic aberration

It has always been thought that 570 nm (yellow) is the preferred wavelength of the eye to focus on the retina (Rabbetts, 2007). Since the logMAR hologram was illuminated using a 633 nm He-Ne laser, the longitudinal chromatic aberration for these two wavelengths has been measured to be about 0.30 D (Figure 3.9) (Howarth & Bradley, 1986; Rynders, Navarro, & Losada, 1998).

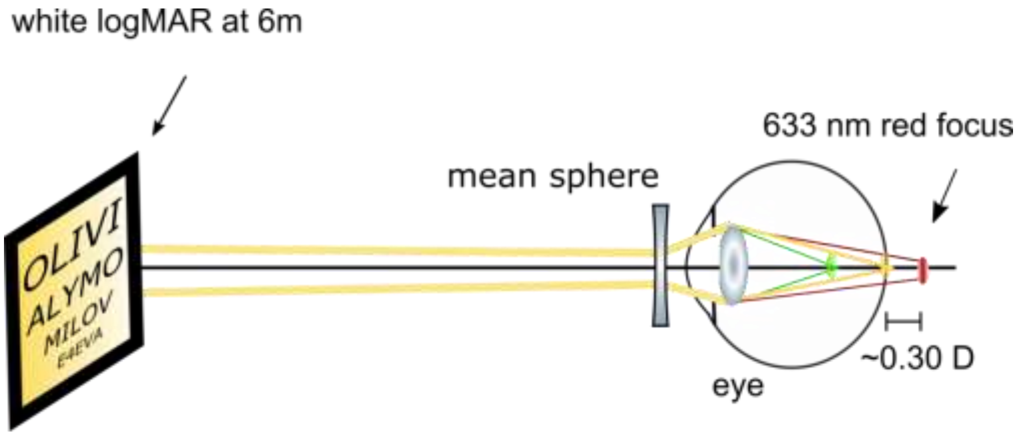


Figure 3.9. Schematic diagram showing the preferred wavelength of focus of the eye (570 nm light) being focused on the retina. The 633 nm focus is located approximately 0.30 D behind the retina.

The expected discrepancy between refraction in polychromatic illumination and 'red' illumination should be 0.30 D. The fact that the mean difference between holographic and conventional refraction was 0.06 D suggests that during holographic refraction, the 633nm focus was also 0.30 D-0.06 = 0.24D behind the retina, with the possibility for subjects to accommodate by this amount (Figure 3.10 and 3.11).

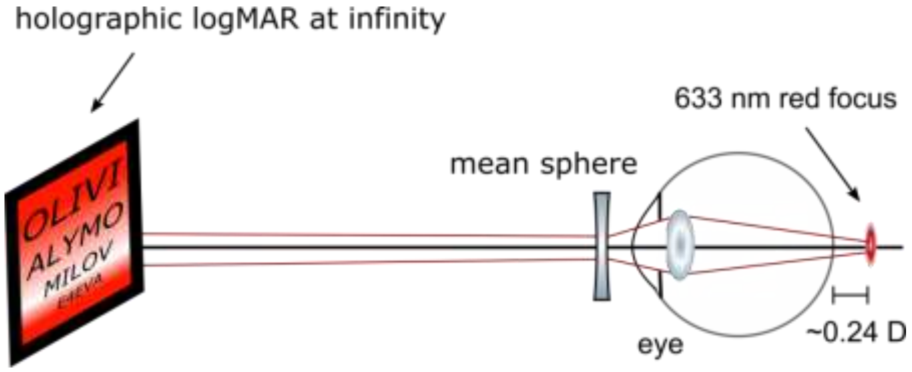


Figure 3.10. After correcting for vergence and chromatic differences between conventional and holographic refraction, the red focuses 0.24 D posterior to the retina.

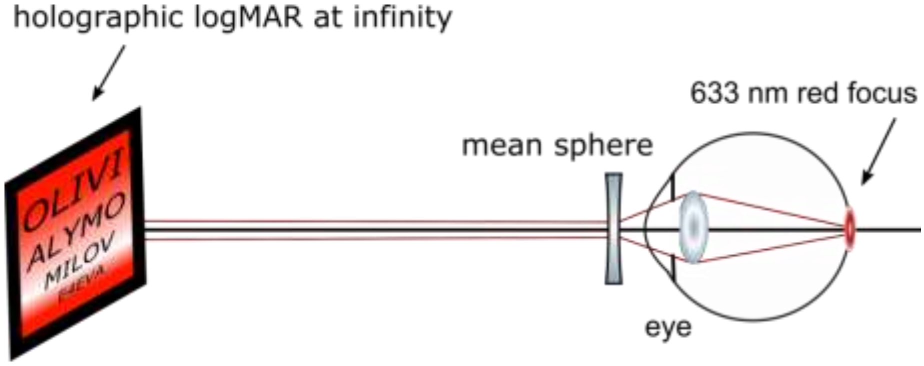


Figure 3.11. Subjects appear to accommodate by an average of 0.24 D to bring the red focus onto the retina for maximum visual acuity.

Put another way, after correcting for object vergence (0.17D) and chromatic differences (0.30D),

(conventional refraction - 0.17) - (holographic refraction - 0.30) = 0 D.

Rearranging the above equation, it is expected that the difference between conventional refraction and holographic refraction = -0.13 D (conventional more negative). However, measured results were 0.11 D, with conventional refractive being more positive. The relative difference of 0.24 D suggests that either conventional refraction was more positive by 0.24D or holographic refraction was more negative by 0.24 D. There have been reports that for distant fixation under white light, there is a tendency for a lead in accommodation(Rabbetts, 2007) or to place the red wavelength on the retina (Ivanoff, 1949; Keirl & Christie, 2007). In both situations, conventional subjective refraction will be more positive and may explain the 0.24 D positive bias between conventional and holographic refraction. The other possible explanation for the 0.24 D positive bias could be that subjects perceived the holographic image to be closer than optical infinity. Although the holographic image was imaged at optical infinity, the confines of the 3-meter consultation room could have resulted in the subject fixating a lot closer than optical infinity. In effect, subjects were accommodating by 0.24D during holographic refraction. A future study might try to determine the cause for the 0.24D discrepancy between holographic and conventional subjective refraction.

3.4.5 Holographic refraction (analysis)

Holographic refraction was started with the eye under optical fog (a trial lens of -0.25 D was shown to the subject, which had the effect of moving the optical image closer to the retina. This reduces the size of the blur circle on the retina and improves vision in the process. Another -0.25 D was added until the subject reported maximum visual acuity, which was when the optical image coincided with the retina. Correcting for vergence distances between six metres in conventional refraction and infinity for holographic refraction (0.17D), as well as the chromatic differences of wavelength between the two methods (0.30D), the expected mean difference should be approximately 0.24D (the measured mean difference of 0.11 D - 0.17 D for a vergence difference of +0.30 D for chromatic difference), with holographic refraction being more negative (or conventional refraction more positive). On average, holographic refraction had a slightly more negative refraction compared to conventional refraction. For fifteen of the subjects (Group 1), the red focus was set close to the retina (mean difference of 0.13D, SD = 0.00 D) suggesting minimal accommodation. However, for the remaining eight out of the twenty-three subjects (Group 2), their vision was improved with another -0.25 D or lower lens (average lens power = 0.45D, SD = 0.12 D) with the average difference between these two groups being 0.31D (p <.0005). This suggests the possibility that these subjects were accommodating during holographic refraction resulting in the acceptance of more minus lenses. Furthermore, the average age of Group 2 (41 years, SD = 17) was higher than that of Group 1 (mean = 21 years, SD = 13), with a mean difference between the two groups being statistically significant (MD = 20 years, standard error = 6.5 years, t(18) = 3.052, P = 0.007). Younger subjects were on average accepting more negative power than the older subjects. In other words, giving an extra -0.25 D to young subjects resulted in an improvement in vision (of two or more letters) that was not apparent with the older group. One possible explanation for this is that the refractive state of the eye may actually have changed, becoming more negative in the younger group (or more positive in the older group). It is speculated that the former was the case, with younger subjects accommodating by a small amount (because of their relatively higher amplitude of accommodation). This suggests that the higher accommodative amplitude of the younger age group might have played a role in the over-minus of holographic refraction.

3.4.6 Effect of over-minus (over correction for myopic subjects, under correction for hyperopic subjects)

During the data collection process when the practitioner was trying to establish the spherical endpoint, subjects are often over-minused intentionally to determine if the lens provides for any improvement to vision. With the logMAR chart in white light, some subjects responded with seeing the letters in the chart clearer/darker and smaller with an extra -0.25 D lens although visual acuity remained the same. This was probably due to accommodation. In contrast to conventional subjective refraction, during holographic refraction, these subjects noticed a slight blur when over-minused. This suggests that these subjects did not accommodate during holographic refraction, resulting in blurriness when over-minused.

Why did an extra -0.25 D lens cause blurring in these subjects in holographic refraction but not in conventional refraction? Why did the eye not accommodate the extra -0.25 D to maintain good visual acuity? Accommodation could be inhibited by a combination of factors including speckle pattern and the monochromatic nature of the illumination light.

When fully corrected and an extra -0.25 D was given monocularly at the spectacle plane (other eye occluded) and under the polychromatic light, the -0.25 D will blur the logMAR, and this provides a negative feedback to the eye to initiate accommodation to increase or maximise the luminance contrast of the retinal image (Switkes, Bradley, & Schor, 1990). This system is a closed-loop with negative feedback and works in the absence of monocular cues, stereopsis, depth perception and chromatic aberration. However, this may not be entirely true for the holographic logMAR chart because of laser speckle. Speckle noise on the image occurs when the coherent light illuminates a diffuse surface, which is quite rough relative to the optical wavelength of light. The image will have multiple dark and light spots that are granular in appearance and these speckles are seen simultaneously with the logMAR characters. Laser speckles are always in sharp focus independent to the refractive state of the eye and, are therefore a poor stimulus for accommodation. It is possible that these speckles were inhibiting the reflex accommodative ability of the eye.

This effect was also observed in a previous study where the authors tried to use a holographic multi-vergence target to measure the amplitude of accommodation (Avudainayagam, Avudainayagam, Nguyen, Chiam, & Truong, 2007). The multi-vergence hologram contained distant and multiple near high-contrast characters with the expectation that young distance-corrected subjects would be able to see distant targets and accommodate to clear near targets as well. The multi-vergence hologram also contained two conflicting images for the eye: large high contrast characters providing negative feedback through the luminance contrast system (when targets are blurred), and small laser speckles, which are always in focus and inhibit reflex accommodation. It was observed that the ubiquitous coherent laser speckles overwhelmed the near-targets in the hologram resulting in young subjects unable to accommodate to see the near high-contrast characters. Subjects were only able to accommodate when an external high contrast reading chart with varying near-character sizes was provided at 40cm.

Furthermore, it is known that in white light the presence of longitudinal chromatic aberration (LCA) facilitates accurate accommodation. Indeed, numerous studies have shown that the amplitude of accommodation was reduced when chromatic aberration was removed either with achromatized light under polychromatic illumination, through the use of monochromatic light or when LCA was reversed (Aggarwala, Nowbotsing, & Kruger, 1995; Kruger, Aggarwala, Bean, & Mathews, 1997; Kruger, Mathews, Katz, Aggarwala, & Nowbotsing, 1997). This suggests that the relative chromatic contrast of the cones can drive reflex accommodation as well. Under polychromatic illumination, when a subject sees a letter chart clearly, the object is conjugate with the retina, with the preferred 'yellow' light of the eye focused on the retina (Figure 3.9), and shorter wavelengths of light forming uncrossed out of focus rays at the retina, and longer wavelengths forming crossed rays but out of focus at the retina. If a positive/negative lens was placed in front of the subject's eye, the view of the chart should become blurred. Since the contrast of the retinal image with different wavelengths specifies focus for the eye (Kruger, Nowbotsing, Aggarwala, & Mathews, 1995), the direction of blur (whether negative or positive) is detected by the eye, and the subject can relax/accommodate to clear the letter chart again if accommodative amplitude is adequate. This reflex accommodation is true for both negative and positive defocus. For this reason, it is easy to over-minus young subjects during refraction in white light because of accommodation, but not over-minus during holographic refraction because of the inhibition of reflex accommodation.

In the holographic logMAR chart, laser light was used for reconstruction. Since laser light is monochromatic in nature, there was no LCA to initiate reflex accommodation. Whilst the logMAR hologram might not replace the traditional letter chart per se, its use of monochromatic lighting and control of accommodation as explained above, makes it a useful addition to an optometrist's repertoire of tests.

Subjective refraction, whether holographic or conventionally done, is often preceded by an objective method (such as retinoscopy or autorefraction). However, this may not always be possible, such as during equipment failure or remote non-clinical settings (domiciliary visits, nursing homes or schools). In these situations, it is possible to use a 'multi-vergence target' in a hologram to obtain the best vision sphere as the starting point for subjective refraction refinement.

Future studies might explore the possibility of cross-checking the final results with the movement of laser speckle. It is well known that laser speckle appears to move with relative movement between speckle interference and retinal image(Ingelstam & Ragnarsson, 1972). If the refractive endpoint is correct, then speckle pattern appears to 'boil' with relative movement of the eye and target.

In the clinical setting, clinicians often also need to measure astigmatism as well as a binocular balance. Further works may also include recording a holographic fan chart or sunburst patterns to aid in the determination of astigmatism (Avudainayagam &

Avudainayagam, 2007). A more convenient method might be to record some ‘concentric rings’ or ‘dots’ together with the logMAR chart to facilitate both spherical and cylinder measurements. Furthermore, by using two separate holograms for the two eyes, it is possible to use successive alternate occlusion to binocular balance.

Holograms are simple to fabricate, long lasting and require no maintenance. Using a master hologram, duplication is easy and relatively inexpensive. The original scene is recorded in the hologram and is reconstructed in its entirety. Chart luminance, testing distance and character contrast are therefore relatively unchanged between repeated reconstructions and use. Furthermore, the gas laser used in this study could be easily replaced with a battery-operated laser diode of the same wavelength, and with minor adjustments to the optics, the technology can be made compact and portable.

Conclusions

3.5

The logMAR hologram has constant chart luminance and distance all under one system, with letter contrast unaffected by room or external illumination. This experiment showed good agreement with conventional refraction and the two methods can be used interchangeably.

The holographic logMAR chart has good control of accommodation by appearing to inhibit both the luminance contrast and chromatic contrast channels for reflex accommodation, making it useful for not only subjective refraction but also for objective systems such as autorefractors. Holograms are compact, inexpensive, portable, long lasting and easy to fabricate and maintain. They definitely have the potential to be used as an alternative to conventional logMAR charts for the purpose of spherical refraction.

This study also demonstrated that even in the presence of laser speckle, the eye is sensitive enough to detect 0.25 D defocus when viewing a logMAR hologram. Furthermore, because the hologram is inhibiting accommodation to a certain extent, over-minusing can result in the blurring of letters in young subjects (instead of young subjects accommodating and reporting clear letters, but just of a smaller and darker appearance).

Chapter 4

Spherical refractive error measurement using a holographic multi-vergence target

Part of this chapter has been submitted and is undergoing peer review:

Nguyen, N. H. N. (2016). *Hologram inhibits the accommodation of young adults*. Manuscript submitted for publication.

In the previous chapter, it was shown that a logMAR hologram can be used to accurately determine the spherical refractive error of the human eye. During the process to determine the spherical refractive error with this hologram, negative spherical lenses were sequentially given until no improvement in vision was found. When too much minus was given, the optical image formed by the eye was posterior to the retina. Subjects could either report the vision with this lens as being 'fuzzier' (because the image was further away from the retina than the previous lens) or 'similar' (when subject accommodated the optical image onto the retina). Since the majority of the young subjects could accommodate, it was expected that most would be able to accommodate and report 'similar' with the over- corrected lens. It was peculiar that this was not the case in the hologram, where subjects found it difficult to accommodate and reported 'fuzzier' vision instead.

This inability to accommodate in a hologram was also observed in my undergraduate final year research project, where it was discovered that subjects found it difficult to accommodate to read closer characters in the hologram. Accommodation was only possible for these subjects when an external high-contrast character was placed at a reading distance to elicit an accommodative response.

It was already established that holographic refraction using a holographic multi-vergence target had good agreement with conventional objective and subjective methods (Avudainayagam, 2007). Please refer to Appendix A for the full paper. The aim of the following experiment was to use a similar holographic multi-vergence target to investigate the ability of the eye to accommodate in the absence of an external accommodative stimulus.

4.1 Introduction

Refractive error of the human eye is often determined subjectively by presenting a lens in front of the eye and asking patients to report their vision of a distant letter chart. Often, the tested eye is under fog, and the minus lens is given sequentially until the clearest vision is attained. Assuming reliable patient responses, when a minus lens is added to a fogged eye, patients can only report one of four possible observations:

1) ‘clearer vision’ as the minus lens shifts the optical image closer to the retina
2) ‘same vision’ as the optical image straddles the retina
3) ‘worse vision’ as the optical image moves away from the retina
4) a ‘smaller and/or darker’ image perception if the patient accommodates to put the optical image onto the retina.

In young subjects where there is ample accommodative amplitude, practitioners would expect more of the ‘smaller and/or darker’ response. On the contrary, the expected response for the over-correction with a negative lens in presbyopes is ‘worse vision’ because of their comparatively limited accommodative ability.

Previously, it was observed that a holographic logMAR chart could inhibit the accommodation of young subjects when attempting to measure their spherical refractive error. When young subjects were over-corrected with a negative lens, some of these subjects reported a blurrier view of the holographic letters instead of the expected ‘smaller and darker’ response.

The research aim was to use the holographic logMAR chart to accurately measure the spherical refractive error of the human eye. It was hypothesised that subjects were able to appreciate small amounts of blur in a holographic logMAR chart to permit accurate spherical refractive error measurements. For accurate measurements to be possible, it was also hypothesised that the monochromatic light from the hologram was inhibiting accommodation for some of these subjects. To test this hypothesis, an optometer with multiple fixed targets at various vergences (MVT) was recorded into a hologram. The MVT hologram was then used to measure the clearest vergence (corresponding to the spherical refractive error) as well as the nearest vergence (corresponding to the maximum accommodative effort) whilst subjects were permitted ample time to freely view of the hologram.

Method

4.1.1 Subject recruitment

Subjects were recruited following the same protocols as applied in Section 2.9.

4.1.2 Conventional subjective refraction

Subjective refraction was carried out on subjects following the same procedure and protocols as applied in Chapter 3.

4.1.3 The holographic multi-vergence target

A holographic multi-vergence target (MVT) is a hologram recording of large high-contrast characters located at multiple vergences from the eye.

4.1.3.1 *Recording the MVT into a Hologram*

Refer to chapter 2 for recording setup.

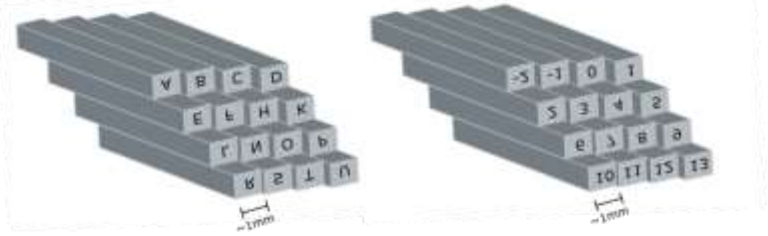


Figure 4.1. Schematic drawing of the object used for holographic recording. Actual objects are made from sticks with printed characters stuck on their ends. The zero vergence corresponds to an inverted ‘A’ for the myopic hologram (left) and ‘0’ for the hyperopic hologram (right).

Figure 4.1 shows a schematic diagram of the two MVTs used for hologram recording with the actual characters used (inverted).

4.1.3.2 *Reconstructing the hologram*

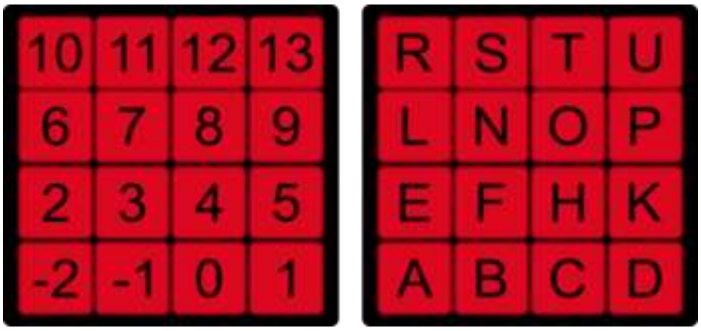
See chapter 2 for a detailed account of hologram reconstruction. For this experiment, the two holograms were used with testing vergences ranging from 0 D to –7.50 DS (to test for myopia) and –1.00 D to +6.50 D (to test for hyperopia). Table **4.1** shows the actual label used and the corresponding measured vergences. Actual label positions can be seen from Figure 4.2.

Table 4.1. The two multi-vergence targets with label used and corresponding measured vergences.

Myopic target		Hyperopic target	
Label	Actual vergence (D) ± 0.10 D	Label	Actual vergence (D) ± 0.10 D
A	-0.03	-2	-1.04
B	-0.57	-1	-0.60
C	-1.08	0	-0.06
D	-1.62	1	0.46
E	-2.09	2	0.88
F	-2.58	3	1.38
H	-3.03	4	1.95
K	-3.59	5	2.32
L	-3.95	6	2.79
N	-4.50	7	3.45
O	-5.08	8	3.94
P	-5.58	9	4.62
R	-5.91	10	4.95
S	-6.44	11	5.48
T	-7.05	12	6.02

U	-7.53	13	6.70

From table 4.1, some of the targets deviated more than the expected measurement error of ±0.10 D. The discrepancy could be from human error which cannot be calculated beforehand. One target (out of 16) from the myopic MVT deviated more than expected (error 0.12 D from intended vergence). Five targets (out of 16) from the hyperopic MVT deviated more than expected. Since the MVT is a 4 x 4 array, if there is one deviating target, the rest of the targets from the same row will also deviate. However, this error has no bearing on the conclusion formed in the study because the actual measured vergences were used.



10	11	12	13
6	7	8	9
2	3	4	5
-2	-1	0	1

R	S	T	U
L	N	O	P
E	F	H	K
A	B	C	D

Figure 4.2. Positioning of the characters in the hyperopic MVT (left) and myopic MVT (right). Only targets with vergence close to the refractive error were visible to the subject.

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4.1.3.3 *Testing procedure*

Refer to chapter 2 for the testing procedure for the holographic MVT. However, for this experiment, no spectacle prescription was worn by the subject whilst viewing through the hologram.

Actual conventional spherical refraction and holographic spherical refraction and accommodation measurements took a few minutes to perform. To reduce the effects of fatigue, subjects were given a few minutes to recover between measurements. One clinician performed both tests, but he was unaware of the target vergence of the MVT hologram. Autorefraction, conventional refraction, and holographic measurements were all performed sequentially (in that order) in one session by one sole practitioner under the same room conditions.

4.1.4 Statistical considerations

Student t-tests were used to assess differences in refractive error between conventional and holographic measurements, as well as to measure the amplitude of accommodation in the hologram. Significance was set at 0.05.

4.2 Results

Data from 31 subjects were used for this experiment. The MVT had a limited vergence range, so subjects with refractive error close to the lower limits of the MVT could not be measured reliably for their amplitude of accommodation. For this reason, these subjects were excluded since one cannot ascertain whether this data was valid.

Table 4.2. Raw data showing age, spherical refractive error, nearest vergence and clearest vergence observed.

Reference	Age (Years)	Spherical error (D)	Nearest vergence reported correctly (D)	Clearest vergence (D)
1	14	-0.01	-0.60	-0.60
2	16	0.75	-0.60	0.88
3	16	-1.00	-5.59	-3.77
4	16	-2.63	-5.58	-2.58
5	16	-3.13	-5.58	-3.50
6	17	0.00	-0.60	-
7	17	-1.38	-4.50	-2.56
8	17	-0.63	-3.59	-1.63
9	17	-1.25	-3.59	-2.09
10	18	-1.25	-3.95	-3.31
11	18	-0.63	-3.59	-1.63
12	19	-3.13	-5.58	-4.22
13	21	-1.63	-0.60	-
14	21	-4.13	-5.08	-3.77
15	29	0.13	-1.04	-
16	30	-2.38	-3.95	-3.31
17	31	-1.25	-1.04	-
18	32	1.00	-0.60	-0.06
19	34	-4.13	-5.58	-3.77
20	35	0.25	-0.06	-
21	45	1.25	-0.06	1.21
22	46	-3.63	-7.53	-4.77
23	47	1.13	1.38	0.88
24	49	1.13	-0.60	0.88
25	50	1.13	0.46	0.88
26	55	0.25	-1.63	-0.56
27	55	1.25	-0.60	0.88
28	61	1.13	0.46	0.88
29	62	1.13	-1.04	0.88
30	64	-3.13	-7.53	-4.77
31	65	1.13	0.46	0.67
Mean	33.32	-0.76	-2.50	-1.49
SD	17.45	1.77	2.60	2.12

From Table 4.2, ‘nearest vergence’ is the vergence located closest to the subject. It is a measure of the amplitude of accommodation (difference from subjective refraction). ‘Clearest vergence’ is the vergence located at the subject’s farpoint and is a measure of the refractive error.

Table 4.3. Descriptive statistics.

	N	Minimum	Maximum	Mean	Std. deviation
Age (years)	31	14	65	33.32	17.45
Spherical error (D)	31	-4.13	1.25	-.76	1.77
Nearest vergence (D)	31	-7.53	1.38	-2.50	2.60
Clearest vergence (D)	26	-4.77	1.21	-1.49	2.12

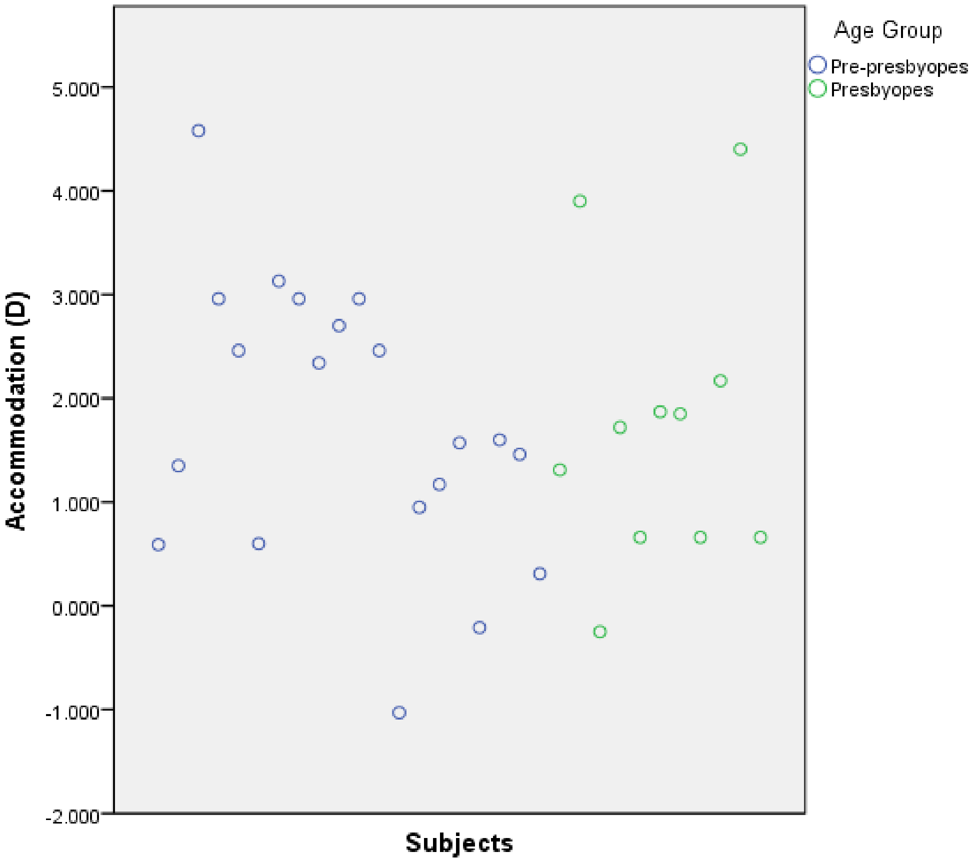

Figure 4.3. Scatter plot showing maximum accommodation possible when freely looking through the hologram. Subjects were ranked according to age (youngest from left).

One of the research aims of the experiment was to determine whether subjects could accommodate when looking into the hologram. To achieve this, subjects were divided into a younger (pre-presbyopic or age ≤ 40) or an older (presbyopic or age > 40) group and their amplitude of accommodation were measured using the hologram. The maximum vergence that subjects could see closer than their optimal far point will be referred to as ‘accommodation’. An independent t-test was conducted to compare the level of accommodation between younger and older age groups. There was no significant difference between the younger (mean = 1.75 D, SD = 1.34 D) and older (mean = 1.72 D, SD = 1.40 D) age groups, with a mean difference of 0.02 D (p = 0.97). The result suggests that younger subjects, on average, were not accommodating any more than the older age group. However, there was high variability within the group.

Table 4.4. Descriptive statistics showing the level of accommodation between a younger and older group when viewing in a hologram.

Age group	Mean accommodation (D)	Std. deviation	Sample size
Pre-presbyopes	1.75	1.34	20
Presbyopes	1.72	1.40	11
Total	1.74	1.34	31

Table 4.5a. Descriptive statistics for the pre-presbyopic group.

Parameter	N	Minimum	Maximum	Mean	Std. deviation
Age (years)	20	14	35	21.70	7.09
Spherical refraction (D)	20	-4.13	+1.00	-1.32	1.52
Accommodation (D)	20	-1.030	4.58	1.75	1.34
Subjective — holography (D)	15	-0.36	2.77	0.80	0.86

Table 4.5b. Descriptive statistics for the presbyopic group.

Parameter	N	Minimum	Maximum	Mean	Std. deviation
Age (years)	11	45	65	54.45	7.54
Spherical Refraction (D)	11	-3.63	+1.25	+0.25	1.82
Accommodation (D)	11	-0.25	4.40	1.72	1.40
Subjective — holography (D)	11	+0.04	+1.64	0.52	0.49

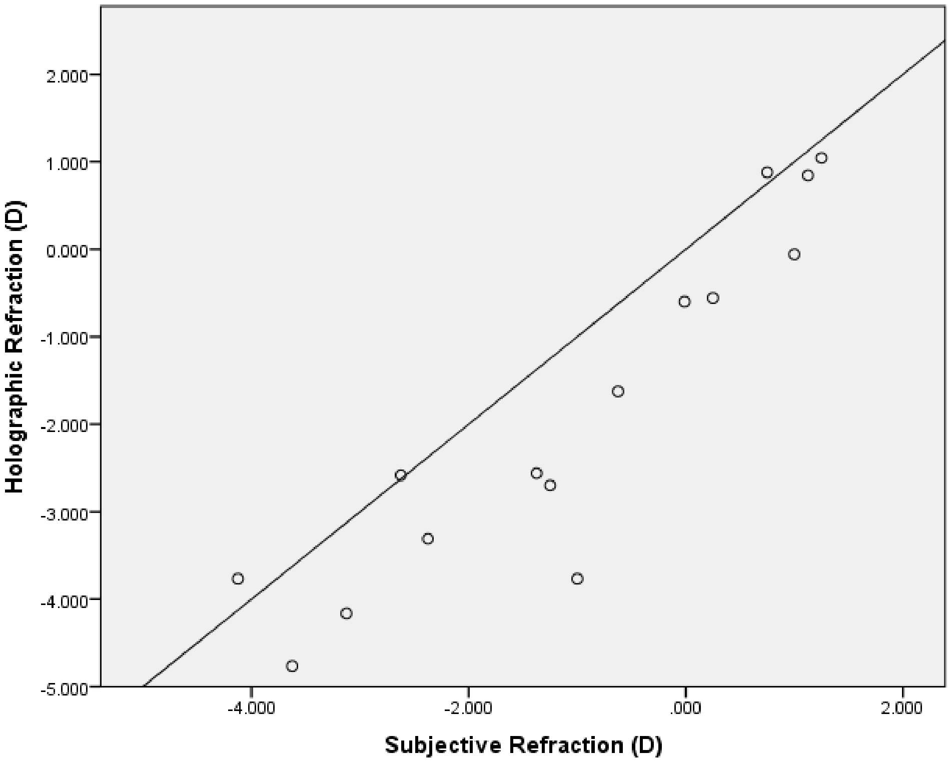

Figure 4.4. Scatter plot (with a line of equality) comparing holographic refraction using an MVT and subjective refraction.

Another aim of this study was to determine whether providing subjects with a prolonged view of the holographic MVT would promote them to accommodate because of multiple near-targets being present.

A paired t-test was therefore conducted to compare the spherical refractive error between the conventional method and the holographic method. There was a significant difference (mean difference = 0.68 D, *P* < 0.001) between conventional refraction (mean = -0.81 D, SD = 1.91 D) and holographic refraction (mean = -1.49 D, SD = 2.12 D). The result suggests that there was slight accommodation when subjects were permitted a prolonged view of the holographic MVT.

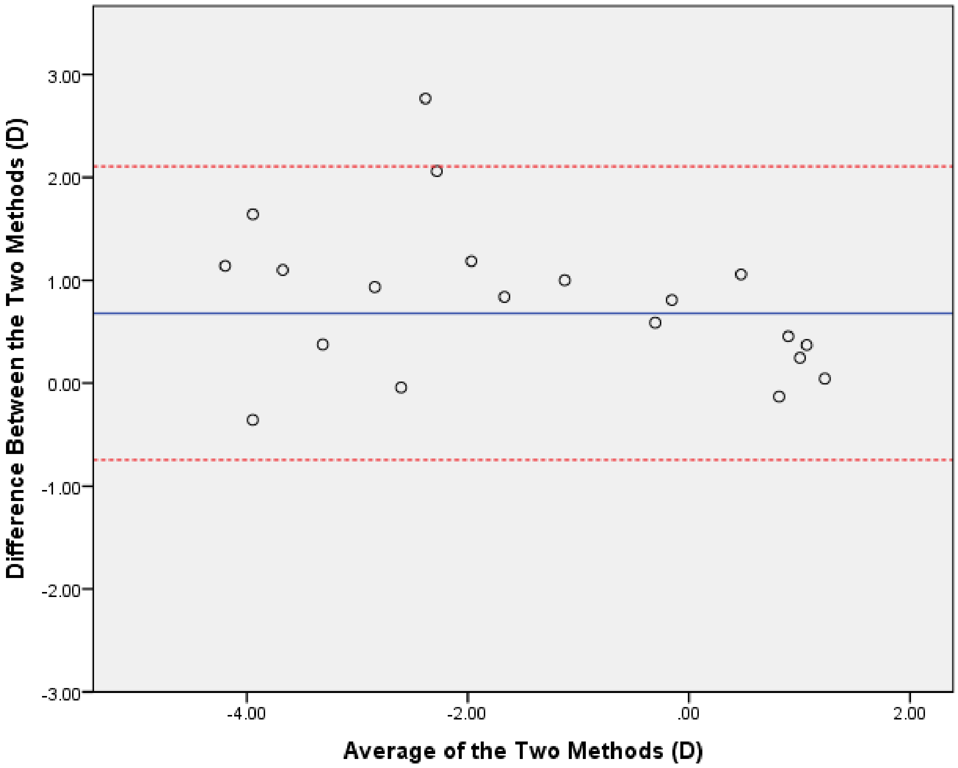

Figure 4.5. Bland-Altman's method showing the mean (solid blue line) and 95% agreement interval (red dotted line). Conventional refraction was on average, more positive than holographic refraction.

By classifying subjects with spherical refractive errors greater than +0.50 DS as hyperopia and subjects with spherical refractive errors lower than -0.50 DS as myopia, it was possible to compare the refractive error measurement and accommodative efforts of these two refractive groups. Using this classification, there were 16 myopic subjects (mean spherical refractive error = -2.20 D, SD = 1.22 D) and 10 hyperopic subjects (mean spherical refractive error = +1.10 D, SD = 0.14 D).

When measuring refractive error in the holographic MVT, on average, myopic subjects were found to have a lower reading (more negative) than hyperopic subjects (when compared to conventional refraction). There was a greater refractive error difference between the two methods in myopic subjects (mean = 0.95 D, SD = 0.87 D) than was found in hyperopic subjects (mean = 0.30 D, SD = 0.31 D), with the difference between statistically significant ($t_{(17)} = 2.557$, $P = 0.02$).

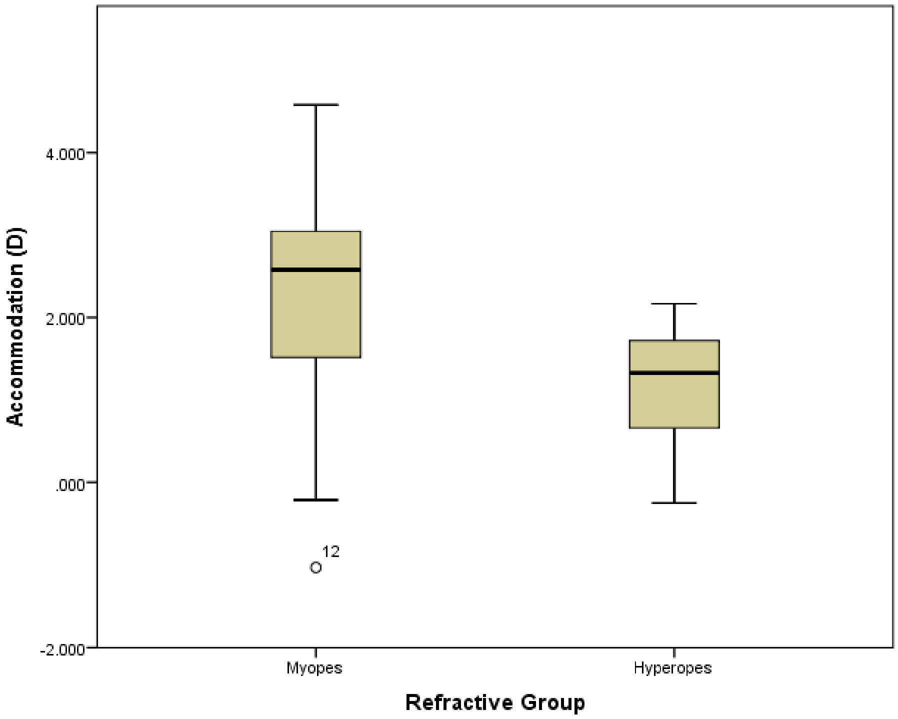

Figure 4.6. Box plot showing myopic and hyperopic refractive groups.

4.3 Discussion

4.3.1 Accommodation in an MVT hologram

The results show that when subjects were able to freely look into a hologram at the MVT, the majority of subjects were unable to fully utilise their accommodation to see the near-targets. Even with encouragement, subjects had a reduced accommodative response in the presence of multiple accommodative stimuli. It appears that the MVT hologram induces insufficient accommodation for these young subjects. This was surprising since some of these subjects are young adults and have more than ample accommodative amplitude to achieve this task under normal white incoherent lighting. In this study, the mean accommodation of the younger group in the hologram was similar to that of the older age group (MD = 0.02 D, $P = 0.97$). The result was confirmed by a poor correlation between age and accommodation in the hologram (Pearson coefficient of -0.19). This is astonishing since it has been well established that the amplitude of accommodation reduces with age (Koretz, Kaufman, Neider, & Goeckner, 1989; Mordi & Ciuffreda, 1998; Ramsdale & Charman, 1989). It was therefore expected that the younger age group would out-perform the older group in the present study.

Subjects in the younger group were typically in their early 20s, and the expected accommodative amplitude for this age group is generally greater than 8 D (Donders, 1864; Duane, 1912). Even when using only half of their accommodative reserves, one would expect this group to have a mean accommodation of at least 4 D (or to be able to recognise letter targets that were 250 mm from their eye). The fact that average accommodation for the younger group was lower than anticipated, and was comparative to the older group (average age of 54 with expected accommodative reserves of 1 D) implies that there was minimal accommodation when trying to accommodate through an MVT hologram, even by young subjects.

In a previously study (Avudainayagam et al., 2007), the writer attempted to measure the accommodation using the MVT hologram. When one of the young authors experimented on himself and tried to accommodate into the hologram, he also had trouble reading the near-targets (just like in this experiment). An external reading chart had to be placed beyond the hologram plate to encourage accommodation. Only then was the amplitude of accommodation assessable with the holographic MVT.

This inhibitive effect on accommodation was also observed in another experiment where young subjects could not accommodate to clear a -0.25 D trial lens when looking at a distant holographic logMAR hologram (Nguyen, in press). This study was able to confirm the previous two observations that although the accommodative reserves were sufficient, most subjects were unable to accommodate in a hologram. The large character size, low target luminance, presence of laser speckle and lack of longitudinal chromatic aberration are all possible contributory factors to inhibiting accommodation in the MVT hologram (Bobier, Campbell, & Hinch, 1992; Kruger, Mathews, Aggarwala, & Sanchez, 1993; Rabbetts, 2007; Rucker & Kruger, 2004).

Figure 4.3 is a scatter plot showing accommodative effort (D) when viewed through the MVT hologram, with subjects ranked according to their age. The results were quite varied, with some young subjects (left side of graph) showing minimal accommodation (~0.50 D) and some showing higher accommodation (~2.50 to 3.00 D). Likewise, for the older presbyopic subjects, some were accommodating poorly (~0.50 D) whilst others accommodated more (closer to 2.00 D). The high variability is confirmed by the large standard deviations in accommodation for the younger group (SD=1.34 D) and the older group (SD = 1.40 D). This suggests that the two groups were not accommodating too differently from each other in the hologram.

A portion of the accommodation measured with the hologram is of the pupillary depth of focus and the ability to recognise large blurry characters. It was a shame that at the time measurements were taken, there was no access to a pupillometer to measure subject’s pupil size, since small miotic pupils might partially be able to explain the better accommodative efforts from some of the older subjects. Some subjects (three subjects) actually had a negative accommodation value (Figure 4.3). This means that instead of being able to read the closer targets, these subjects were actually reading more positive vergences (compared to subjective refraction). The interesting data-point was for the younger subject (i.e. age in the early 20s), where the accommodation was about -1.00 D. Since accommodation was taken as the difference between the vergence measured in the MVT hologram and subjective refraction. Since negative accommodation does not make sense, this might have been due to over-minus of the subject by at least 1 D when performing subjective refraction using the refractor. This has been observed before while performing refraction with a phoropter on some patients (Benjamin, 2006).

It was already established in Chapter 3 that holographic refraction will be more positive when compared to conventional refraction (like that used here) because of differences in chromatic wavelengths and object vergences (Nguyen, in press). Polychromatic light consists of different wavelengths of light. They disperse differently at the retina and this difference needs to be considered since hologram light is ‘red’ and subjective refraction is ‘white’. To quantify ‘accommodation’, the holographic refraction is subtracted from the subjective refraction. But since a correction factor of +0.13 D to the holographic refraction was needed for chromatic and vergence differences, accommodation values were slightly lower than those actually measured. This might explain the very small negative accommodation for the two subjects. Since the vergence correction was so small (0.13 D) and applied to all subjects, this negligible systematic error was not corrected in the data analysis.

There are advantages to the reduced ability to accommodate in an MVT hologram. Instrumental myopia would be reduced, which makes this technique useful as a targeting system for autorefractors. Young patients looking into an enclosed autorefractor with a holographic target will not be able to accommodate liberally and this may improve the accuracy of autorefractor measurements. Such a system might flash the MVT hologram on and off repeatedly or make use of a large holographic character located at a single vergence.

4.3.2 Refractive error measurement using an MVT hologram

Most of the measurements performed using the hologram were more negative than those arising from subjective refraction (Figure 4.4). On average, the discrepancy was slightly greater in the pre-presbyopic or younger group (mean = 0.80 D, SD = 0.86 D) than the presbyopic or older group (mean = 0.52 D, SD 0.49 D). However, the difference did not reach statistical significance ($F_{(1,24)}$ = 0.97, *ns*). This lead in accommodation was observed across all ages, with a low correlation coefficient (−0.23). The level of agreement was assessed using Bland-Altman's method (Bland & Altman, 1986). There was a positive bias of 0.68 D (i.e. the hologram method was more negative or the subjective refraction method was more positive), with a 95% agreement interval of 2.85 D (Figure 4.5).

In a previous study (Avudainayagam et al., 2007), subjects were briefly flashed with a view of the MVT in a hologram and they were then asked to report the clearest character/s seen. Subjects were exposed to the hologram for durations of about one second, which is long enough to inhibit any accommodation (Heron & Winn, 1989; Tucker & Charman, 1979). Holographic refraction using this protocol had good agreement with standard methods (mean difference = 0.07 D, 95% agreement interval of 1.53 D). This experiment differs in the duration the MVT hologram was presented to subjects. Subjects were allowed to freely view the hologram without interruptions and it appeared that by giving subjects ample time to observe the hologram; this changes the preferred focussing of the eye in a hologram. The possibility of a slight lead of accommodation when fixating a distant light has been suggested by others (Ivanoff, 1949; Keirl & Christie, 2007; Rabbetts, 2007), and was discussed in detail in Chapter 3. Similarly, it appeared that when looking into a holographic MVT for brief periods, accommodation remained relaxed and there was good agreement with conventional subjective refraction (Avudainayagam et al., 2007). However, if patients were allowed ample time to observe the MVT, subjects would, on average, prefer to have a slight accommodative lead (0.68 D). A flash-on-off method is therefore recommended when the holographic MVT is used to measure refractive error, since permitting subjects liberal time to view the hologram resulted in poorer agreement with conventional methods.

Why are younger subjects having trouble accommodating down the holographic MVT when their accommodative amplitude is plentiful? The answer could be because of laser speckle and a lack of longitudinal chromatic aberration resulting in poor accommodative abilities (Aggarwala et al., 1995; Kruger, Aggarwala, et al., 1997; Kruger, Mathews, et al., 1997). This was already discussed in detail in Chapter 3.

One problem with the experiment which was only realised after completion was the fact that many subjects could read to the end of the MVT. The myopic MVT had a range from 0.00 D to -5.00 D and hyperopic MVT had a vergence range from -1.00 D to +4.00 D. When subjects were asked to report their vision whilst looking through the hologram, those with refractive errors close to the limit of these ranges could probably read more if there were sufficient targets beyond these vergences. The limited dioptric range of the MVT meant that these subjects had to be excluded. For future studies, extending the range of the MVT to include a wider range of vergences may be one solution; however, a greater range requires a larger object, which is more difficult to record into a hologram. An alternative solution might be to use trial lenses to extend the range of the MVT. As an example, a +1.00 D might be able to extend the higher range (less negative) of the myopic target, or a -1.00 D lens would permit subjects to read more from the lower range (more negative) of the myopic target. Another advantage of using trial lenses together with the MVT hologram is that only one hologram is required. In theory, the practitioner should be able to partially correct the subject using trial lenses until subjects start to register characters near the dioptric midpoint of the MVT hologram. In a clinical setting, this could be simpler than having two holograms around. In a research setting, this permits both myopic and hyperopic subjects to be tested using one hologram rather than using two holograms that may or may not have different reconstruction efficiencies.

Future studies might look at the possibility to measure the dark focus using the MVT hologram. The eye tends to return to an intermediate resting position (dark focus) when the image to focus is degraded (Leibowitz & Owens, 1978). This shift varies considerably between individuals and can be quite significant during low lighting conditions such as driving at night in rural areas, with myopic shifts as high as from 0.75 D to 1.50 D (Artal et al., 2012; Leibowitz & Owens, 1978). By adapting subjects in total darkness and briefly presenting a distance-corrected subject to the MVT hologram, it might be possible to measure the dark-focus.

4.3.3 Difference between refractive groups

It was interesting to see that myopic subjects were behaving differently to hyperopic subjects in the hologram. During spherical refractive error measurements, myopic subjects had a greater lead of accommodation compared to hyperopic subjects (MD = 0.65D, $p < .02$). When trying to accommodate down the MVT as much as possible, myopic subjects appeared to be able to perform slightly better than hyperopic subjects (MD = 1.18 D, $P = 0.03$). This was represented visually in Figure 4.6. The average age for the myopic group was lower (mean = 25 years old, SD = 13 years) compared to the hyperopic group (mean = 48 years old, SD = 15 years). It is unknown whether the lower average age of the myopic group would have given this group an advantage with respect to the greater level of accommodation measured in the hologram. The low Pearson Correlation Coefficient between age and the lead in accommodation for myopic subjects (0.07) and hyperopic subjects (0.09) as well as the fact that the MVT hologram induced ‘accommodative insufficiency’ in young subjects would suggest a low association.

Another important consideration is the difference in ocular accommodative demand for spectacle-corrected ametropia. The ocular accommodation is accommodation measured at the level of the eye (corneal plane). This is different to spectacle-accommodation, which is measured at the spectacle plane. Usually in clinic, patients are distance-corrected and their spectacle accommodation is measured. This spectacle accommodation should be converted to ocular accommodation because for the same spectacle accommodation, the ocular accommodative demand will be lower for a spectacle wearing myope and higher for a spectacle wearing hyperope. However, in this study, subjects were not distance-corrected, and so the MVT hologram was already measuring the ocular accommodation. No adjustment from spectacle to ocular accommodation was required. Since trial lenses were not used to correct the subject's ametropia, this effect can be ignored.

In addition to the vergence change between refractive groups when looking through corrective lenses, there are also differences in convergence demand between refractive groups due to induced prismatic effect from the trial lens (base-in for myopic subjects, base-out for hyperopic subjects). However, this effect can be ignored in this thesis because testing was done monocularly.

4.4 Conclusions

In a previous study, the hologram of an MVT when used with an external reading chart, could be used to successfully measure the amplitude of accommodation (Avudainayagam et al., 2007). This study showed that in the absence of an external reading chart, the ability to accommodate in the hologram to look at the near-targets was reduced dramatically.

Furthermore, when using the MVT for spherical refractive error measurement, the holographic reconstruction should be presented for brief periods (~1 s) while fixating on a distant target rather than leaving the holographic reconstruction on indefinitely. On average, subjects tended to accommodate slightly when viewing through the hologram of an MVT, with myopic subjects accommodating more than hyperopic subjects.

Differentiation of myopia and hyperopia using holography

Chapter 5

This chapter has been published as follows:

Nguyen, N., Avudainayagam, C. S., & Avudainayagam, K. V. (2012). An experimental investigation of the vision of hyperopes and myopes using a hologram. *Biomed Opt Express, 3*(6), 1173-1181.

Part of this research has been presented at conferences as:

K. V. Avudainayagam, C. S. A., and N. Nguyen. (2008). *Holographic multi-vergence target throws more light on the vision of hyperopes.* Paper presented at the ICO-21 Proceedings, Sydney.

Please see Appendix B for the abstract.

Introduction

5.1

In the previous chapter, two different holograms were used: one to measure myopia and another to measure hyperopia. A difference in the behaviour of the two refractive groups was discovered whereby myopic subjects were accommodating by an amount greater than hyperopic subjects (when measured with the MVT hologram). However, these two holograms may have different diffraction efficiencies, which would have somewhat biased the measurements. Also, looking closely at the actual vergences for the two holograms (Table **4.1**), there was some error in positioning the 'sticks' during fabrication of the MVT. This resulted in targets having vergences that were measuring either under or over their intended vergence. The systematic error between the two holograms would be different, and this makes comparing data from the two holograms unreliable. To eliminate any doubt and to establish if there is a genuine difference in the behaviour of myopic and hyperopic subjects when viewing through the hologram, the writer decided to distance-correct all subjects and test them using a single hologram. Please see the discussion section of this chapter for further consideration on this point.

A specially designed 3-D target hologram has previously been used to measure the spherical refractive error of various subjects (Avudainayagam & Avudainayagam, 2003, 2007; Avudainayagam et al., 2007). The hologram, when appropriately illuminated by a laser beam, will reconstruct the images of various integers situated at different vergences from a subject's eye. The average vergence of integers seen clearly by the subject through the hologram is used to determine the subject's spherical refractive error. In this chapter, the vision under positive blur for various spectacle-corrected subjects when viewing through the 3-D hologram was investigated. The results indicate that spectacle-corrected hyperopic subjects tolerated more positive blur than spectacle-corrected myopic subjects in recognising the numbers seen through the hologram. That is, the limit of positive blur (or PBL) where character recognition was still possible was lower in myopic subjects compared to in hyperopic subjects.

In order to determine whether the coherent nature of the laser illumination of the hologram was the cause of the difference observed between myopic and hyperopic subjects, the writer simulated positive blur using lenses and tested the vision of subjects under white incoherent illumination. Spectacle-corrected subjects were seated behind a refractor and asked to view a distant letter chart under white light illumination as positive lenses were introduced to blur the eye. Standard ‘60-meter’ (50’) numerals were used to test the subjects, which was consistent with the character angular size in the hologram. No difference in PBL was observed between refractive groups under white light illumination for the recognition of large size standard numbers. This is consistent with results obtained by researchers in the past regarding the effect of positive defocus on blur sensitivity in myopic subjects and non-myopic subjects (Radhakrishnan, Pardhan, Calver, & O'Leary, 2004). Initial findings from the experiments conducted were presented at conferences (Avudainayagam, 2008; N. Nguyen, 2009) and published in *Biomedical Optics Express* (Nguyen, Avudainayagam, & Avudainayagam, 2012). This chapter presents the details of the investigations, the data collected and the results obtained.

The research aim was to investigate the vision under positive blur for various spectacle-corrected subjects when viewing through the 3-D hologram. It was hypothesised that accommodation was triggered in some subjects when looking at the MVT hologram to result in a low limit to positive blur.

The hologram of a multi-vergence target
5.2

The special 3-D target that was used to record this hologram is shown in Figure 5.1. It consists of an array of 16 sticks (2 mm × 2 mm in cross-section) arranged as shown in Figure 5.1. The 3-D target Printed inverted images of test integers were pasted on one end of these sticks. The sticks in the 3-D target were arranged at calculated distances such that when the target was placed in front of a +20 D lens, the vergences of the rays leaving the lens from the various numbers were in the range of +1.0 D to -6.5 D in steps of 0.50 D.

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Figure 5.1. The 3-D target.

Please see Chapter 2 for further information on hologram recording and hologram testing procedures.

Subject selection

5.3

Sixty subjects, ranging in age from 9 to 58 years, were included in the study with the hologram and 39 subjects were included in the study with white light. Ethics approval was obtained from the UNSW Human Research Ethics Committee. Informed consent was obtained from the subject or their parent, depending on the age of the subject. The spectacle correction for the subject was determined by subjective refraction using a refractor. The maximum plus lens for best visual acuity was the criterion for the subjective end point. The mean spherical refractive error of the subjects ranged from −8.00 D to +4.25 D. Only subjects having an astigmatism ≤0.50 D were selected. Subjects with mean spherical refractive errors in the range of −0.25 D to +0.25 D were considered as emmetropic in this study for the purpose of comparing the vision of hyperopic and myopic subjects. The best corrected visual acuity was 6/7.5 or greater, and the subjects had no significant pathology. The vision cut-off was set at 6/7.5 to ensure that a subject misreading one or two letters on the 6/6 line would not be excluded from this study. All subjects easily passed the vision screening criterion. For all of the subjects, the left eye was tested under mesopic conditions.

5.4

Measurement procedure

5.4.1 Auto-refraction and conventional refraction measurements

Auto-refraction and subjective refraction were carried out on subjects following the same procedures and protocols as applied in Chapter 3.

5.4.2 Using the hologram

Please refer to chapter 2 for procedures to use the hologram.

5.4.3 Using a test chart under white light illumination

In the standard refractor arrangement, the subject was given an additional positive lens of power +3.00 DS over and above his/her spectacle correction and presented with three high contrast ‘60-meter’ numerals (50’) at 6 m (20 feet) under white light illumination using a projection chart. If the subject was unable to identify two of the three numbers shown, the power of the additional positive lens was reduced in steps of 0.25 D until he/she could identify two of the three numerals shown. The power of the additional lens when recognition takes place then gave a measure of the PBL for recognition of 50’ (60-metre) numbers under white light illumination.

Autorefraction, conventional refraction, white light measurements and holographic measurements were all performed sequentially (in that order) in one session by one sole practitioner under the same room conditions.

5.5

Results

The 3-D target was designed so that the vergences of various numbers seen through the hologram would vary from −1.00 D to +6.50 D at the eye in 0.50 D steps. However, after the target was fabricated and the hologram was recorded, the vergences obtained at the eye for various numbers were slightly different. The vergences of the integers at the eye were measured objectively in a separate experiment. The designed values and the measured values of the vergences for the first eight numbers are given in Table 5.1. No subject could recognise beyond the 8th number.

Table 5.1. Vergences for various integers in the multi-vergence target.

Number	Designed vergence (Dioptre)	Measured vergence (Dioptre)
−2	−1.00	−1.04
−1	−0.50	−0.60
0	+0.00	−0.06
1	+0.50	+0.46
2	+1.00	+0.88
3	+1.50	+1.38
4	+2.00	+1.95
5	+2.50	+2.32

The results obtained for the PBL in the recognition of integers seen through the hologram were tabulated for 19 myopic subjects, 19 hyperopic subjects, and 18 emmetropic subjects. For subjects who had astigmatism of 0.25 D, the mean sphere given was more positive by 0.125 D, as spherical lenses were not available in +0.125 DS steps in the trial set. This implies that these subjects were tolerating +0.125 DS more blur than that indicated by the number, with most positive vergence recognised by the subject in the hologram. No correction was given since a sphere that was 0.125 D less than the mean sphere could have stimulated the subjects’ accommodation.

Table 5.2. Data obtained with the hologram for myopic subjects.

Serial number	Age (years)	Mean sphere of the spectacle correction (Dioptre)	Integer with most positive vergence recognised	PBL through the hologram[a] (Dioptre)
1	25	−7.625	2	1.005
2	11	−3.25	4	1.95
3	19	−3.25	3	1.38
4	11	−2.875	1	0.585
5	31	−2.375	1	0.585
6	20	−2.25	2	0.88
7	11	−1.50	3	1.38
8	17	−1.375	1	0.585
9	18	−1.375	2	1.005
10	29	−1.25	2	0.88
11	35	−1.25	4	1.95
12	32	−1.125	3	1.505
13	14	−1.00	3	1.38
14	21	−1.00	2	0.88
15	46	−0.75	4	1.95
16	19	−0.50	1	0.46
17	42	−0.50	2	0.88
18	33	−0.375	1	0.585
19	35	-0.375	2	0.88
[a]Mean, 1.09 D; Std dev, 0.49 D.				

Table 5.3. Data obtained with the hologram for hyperopic subjects.

Serial number	Ages (years)	Mean sphere of the spectacle correction (Dioptres)	Integer with most positive vergence recognised	PBL through the hologram[α] (Dioptre)
1	12	0.375	4	2.075
2	51	0.375	5	2.445
3	10	0.50	4	1.95
4	13	0.50	5	2.32
5	43	0.50	2	0.88
6	57	0.50	4	1.95
7	51	0.625	4	2.075
8	45	0.75	4	1.95
9	40	1.00	4	1.95
10	58	1.125	2	1.005
11	38	1.25	5	2.32
12	15	1.50	2	0.88
13	51	1.75	4	1.95
14	51	1.75	5	2.32
15	50	2.125	4	2.075
16	52	2.25	5	2.32
17	55	2.25	5	2.32
18	55	2.25	5	2.32
19	28	4.25	5	2.32

[a] Mean, 1.97 D; Std dev, 0.50 D.

Table 5.4. Data obtained with the hologram for emmetropic subjects.

Serial number	Age (years)	Mean sphere of the spectacle correction (Dioptre)	Integer with most positive vergence recognised	PBL through the hologram[a] (Dioptre)
1	46	−0.25	4	1.95
2	49	−0.25	4	1.95
3	9	0.00	1	0.46
4	13	0.00	2	0.88
5	26	0.00	2	0.88
6	28	0.00	2	0.88
7	33	0.00	4	1.95
8	9	0.00	1	0.46
9	15	0.00	4	1.95
10	17	0.00	2	0.88
11	11	0.25	5	2.32
12	13	0.25	4	1.95
13	25	0.25	1	0.46
14	52	0.25	4	1.95
15	53	0.25	4	1.95
16	56	0.25	3	1.38
17	16	0.25	1	0.46
18	15	0.25	4	1.95

[a] Mean, 1.37 D; Std dev, 0.68 D.

The data on the mean PBL obtained for myopic and hyperopic subjects viewing through the hologram are presented in table 5.2 and 5.3. The mean PBL for myopic subjects was 1.09 D and for hyperopic subjects was 1.97 D. The PBL for hyperopic subjects was 0.88 D more than that for myopic subjects when they see through the hologram. A student t-test (2-tail) for the observed difference in the mean showed that this difference was statistically significant ($P < 0.001$). The data obtained for the PBL with the hologram for emmetropic subjects is given in Table 5.4. The PBL for some emmetropic subjects was like that of hyperopic subjects and for others it was like that of myopic subjects. The mean value of the PBL for these subjects was 1.37 D, and it was closer to that of myopic subjects than that of hyperopic subjects. A plot of the PBL that was obtained for all of the subjects seeing through the hologram and the mean values for each refractive group are shown in Figure 5.2 starting with the most myopic subject on the left and ending with the most hyperopic subject on the right. This plot aids readers to visualise the PBL for various refractive groups. The mean PBL for each refractive group is indicated by the dashed lines. The figure shows that the level of PBL for hyperopic subjects was greater than that for myopic subjects when seeing through the hologram.

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Figure 5.2. PBL obtained with the hologram.

The data obtained on the PBL for myopic and hyperopic subjects viewing ‘60-meter’ (50’) numerals in white light illumination through a refractor with positive lenses to blur at the eye are given in Table 5.5 and 5.6. The difference in the mean PBL between these two groups was only 0.21 D and this difference was not statistically significant ($p = 0.08$).

The data obtained on the PBL with white light for emmetropic subjects are given in Table 5.7. With white light illumination, the mean PBL for all of the refractive groups was more or less the same with the mean value for myopic subjects at 1.96 D, for hyperopic subjects at 1.75 D and for emmetropic subjects at 1.59 D. A plot of the PBL that was obtained in white light for all of the subjects as well as the mean values for each refractive group are shown in Figure 5.3, starting with the most myopic subject on the left and ending with the most hyperopic subject on the right.

Table 5.5. Data obtained in white light for myopic subjects.

Serial number	**Age (years)**	**Mean sphere of the spectacle correction (Dioptre)**	**PBL in white light**^{a} **(Dioptre)**
1	22	−5.50	1.75
2	39	−4.75	2.00
3	21	−3.75	1.75
4	19	−3.625	1.75
5	12	−2.00	2.25
6	13	−1.50	2.00
7	40	−1.375	2.25
8	43	−0.625	1.75
9	32	−0.50	1.75
10	35	−0.50	2.50
11	32	−0.375	1.75
12	36	−0.375	2.00
^{a}Mean, 1.96 D; Std dev, 0.26 D			

Table 5.6. Data obtained in white light for hyperopic subjects.

Serial number	Age (years)	Mean sphere of the spectacle correction (Dioptre)	PBL in white light[a] (Dioptre)
1	35	0.375	1.25
2	51	0.375	1.50
3	33	0.375	1.75
4	30	0.375	2.25
5	43	0.50	1.75
6	41	0.75	1.75
7	58	0.75	2.00
8	17	0.75	2.00
9	43	0.875	1.75
10	51	1.25	1.25
11	51	1.25	1.50
12	55	1.75	2.00
13	46	1.75	2.00
[a]Mean, 1.75 D; Std dev, 0.31 D.			

Table 5.7. Data obtained in white light for emmetropic subjects.

Serial number	Age (years)	Mean sphere f the spectacle correction (Dioptre)	PBL in white light[a] (Dioptre)
1	46	-0.125	1.00
2	36	−0.125	1.75
3	29	−0.125	1.25
4	27	−0.125	2.00
5	9	0.00	1.25
6	11	0.00	2.00
7	13	0.00	1.75
8	50	0.00	2.00
9	14	0.125	1.50
10	38	0.125	1.75
11	11	0.125	1.75
12	17	0.125	1.50
13	37	0.125	1.75
14	35	0.125	1.00

[a] Mean, 1.59 D; Std dev, 0.35 D.

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Figure 5.3. PBL in white light.

Discussion

5.6

Of the subjects that took part in the study, only four myopic subjects, four hyperopic subjects, and four emmetropic subjects had an astigmatism of 0.5 D, while the rest of the subjects had little (0.25 D) or no astigmatism. The difference in the mean PBL of hyperopic and myopic subjects was 0.79 D when these subjects were excluded. The difference remained statistically significant with a *P*-value of less than 0.001. The mean PBL for all the refractive groups was negligibly affected by the exclusion of these subjects.

Using the same subjects for both white and hologram measurements would have required fewer subject numbers. However, disadvantages include more subject fatigue and practitioner bias. The methodology used in this study was sound. A smaller sample size was required for testing under white lighting because refraction was less variable (smaller SD) than testing with a hologram (higher SD). In other words, a smaller sample size did not reduce the power significantly. The difference between myopic and hyperopic subjects when testing under white light nearly made statistical significance ($P = 0.08$). A large enough sample size would eventually help see the difference reach statistical significance. Even if statistical significance was reached in the white light testing group, the difference between the two groups was only 0.21D, which would still have little clinical significance. The difference observed in the hologram was close to 0.80D ($P < 0.05$) and has greater clinical significance.

To determine whether age was a factor for the observed difference in the mean PBL of hyperopic and myopic subjects viewing through the hologram, the writer selected from the measured subjects the 7 hyperopic subjects in the age range of 10 to 40 years and 7 age-matched myopic subjects. The mean difference in the PBL between the two groups was 0.88 D and it continued to be statistically significant with a *P*-value of 0.0035. Thus, the observed difference was not an age-related effect. Further, within each group, age had poor correlation to the PBL. The Pearson Correlation Coefficient between the age and the PBL was 0.13 for myopic subjects and 0.10 for hyperopic subjects.

As all the subjects were measured under the same illumination conditions and refractive group included subjects of all age groups, the observed phenomenon does not appear to be an effect of pupil size. Unfortunately, in this study, pupil size was not measured so the effect of pupil size on PBL remains unknown.

In Chapter 4, the clarity of the characters in the MVT hologram was used to determine the subject's spherical refractive error. The results of this assessment showed that myopic subjects were slightly accommodating more than hyperopic subjects (MD = 0.56 D, $p < 0.02$). Asking subjects to identify 'clear' characters was very subjective and using two different holograms with potentially different diffraction efficiencies may have also biased the results. In this study, a slightly more objective criterion was used, whereby all subjects were distance-corrected, and using a single hologram, subjects were asked to report all the characters recognisable. Subjects were encouraged to read as high in the MVT corresponding to more positive vergences and minimal (if any) accommodation. Also in Chapter 4, accommodation was measured while using the MVT hologram (as discussed in Section 4.3.1). However, it should be appreciated that the main interest of this thesis was in the possible involuntary accommodation (IA). This IA varies considerably between individuals, but was observed to be higher in myopic subjects (compared to hyperopic and emmetropic subjects).

If subjects were to be distance-corrected and then asked to view into the MVT hologram, they should be able to recognise the zero vergence test-target, as well as some others in close proximity to it. Multiple test characters are usually recognisable because of the large character size (50') and because of the pupillary depth of focus.

The ocular accommodative demand is greater for hyperopes and less for myopes when viewing a real object when the ametropia is corrected with spectacles. This is the opposite for virtual objects, where the negative accommodative demand is smaller in myopes than hyperopes. Hypothetically speaking, a +1 D PBL measured by the hologram means that the object vergence +1 D from the spectacle plane. A measured PBL of +1 D in a -7.63 D myopic subject (distance-corrected) would actually be only +0.82 D. Since negative accommodation is not possible, this will manifest positive blur to the subject. Using trial lenses to correct the ametropia, one would then expect for a lower PBL in a myopic subject (higher PBL in a hyperopic subject). Table 5.8 and Table 5.9 show the recalculated PBL after adjusting for the effect of spectacle-correction on PBL.

Table 5.8. Recalculated PBL after adjusting for the effect of wearing spectacles at a vertex distance of 14 mm (for myopic subjects)

Serial Number	Mean Sphere (D)	Measured PBL (D)	Adjusted PBL (D)
1	-7.63	1.01	0.82
2	-3.25	1.95	1.78
3	-3.25	1.38	1.26
4	-2.88	0.59	0.55
5	-2.38	0.59	0.55
6	-2.25	0.88	0.83
7	-1.50	1.38	1.32
8	-1.38	0.59	0.57
9	-1.38	1.01	0.97
10	-1.25	0.88	0.85
11	-1.25	1.95	1.88
12	-1.13	1.51	1.46
13	-1.00	1.38	1.34
14	-1.00	0.88	0.86
15	-0.75	1.95	1.91
16	-0.50	0.46	0.45
17	-0.50	0.88	0.87
18	-0.38	0.59	0.58
19	-0.38	0.88	0.87
Mean	-1.79	1.07	1.04
SD	1.67	0.47	0.47

Table 5.9. Recalculated PBL adjusting for the effect of wearing spectacles at a vertex distance of 14 mm (for hyperopic subjects)

Serial Number	Mean Sphere (D)	Measured PBL (D)	Adjusted PBL (D)
1	0.38	2.08	2.10
2	0.38	2.45	2.48
3	0.50	1.95	1.98
4	0.50	2.32	2.35
5	0.50	0.88	0.89
6	0.50	1.95	1.98
7	0.63	2.08	2.12
8	0.75	1.95	1.99
9	1.00	1.95	2.01
10	1.13	1.01	1.04
11	1.25	2.32	2.40
12	1.50	0.88	0.92
13	1.75	1.95	2.05
14	1.75	2.32	2.44
15	2.13	2.08	2.21
16	2.25	2.32	2.48
17	2.25	2.32	2.48
18	2.25	2.32	2.48
19	4.25	2.32	2.63
Mean	1.35	1.92	2.05
SD	0.99	0.47	0.53

The recalculated PBL resulted in a greater difference between the two refractive groups and was still statistically significant (mean difference = 1.02 D, $P < 0.0001$).

In this study, the mean PBL measured for myopic subjects was both clinically and statistically lower than hyperopic subjects (mean difference = 0.88 D, $P < 0.001$). Possible explanations could be that myopic subjects were accommodating by 0.88 D in an MVT hologram, or the hologram was measuring some latent hyperopia (hyperopic subjects were relaxing latent accommodation by 0.88 D in an MVT hologram), or a combination of the two. If the former is true, then it would confirm the results of my previous experiment where the writer found myopic subjects had a lead in accommodation when permitted ample time to freely observe a holographic MVT (Chapter 4). Please note that this was not observed when the holographic MVT was briefly revealed to subjects by flashing the hologram on (for about 1 sec) then quickly off (Avudainayagam et al., 2007). This accommodation of myopic subjects was limited to a holographic MVT and was not observed in a holographic logMAR chart (Chapter 3). There was also other evidence to support the theory of myopic subjects accommodating based on visual inspection of Figure 5.2 and Figure 5.3. In Figure 5.3, the mean PBL measured with lenses using white incoherent illumination was approximately 2 D across all groups. However, from Figure 5.2, the mean PBL for myopic subjects (~1.1 D) was reduced significantly compared to that for hyperopic subjects (still ~2 D), while the mean PBL for emmetropic subjects (~1.4 D) was in-between that of myopic and hyperopic subjects.

It was speculated that the difference observed between the two main refractive groups (myopia, hyperopia) was due to the multi-vergence nature of the target when viewed through the hologram. The multi-vergence target provides images of test characters in the virtual range of vision for the eye. Chromatic aberration is absent when viewing through the hologram. Therefore, there is no trigger to accommodation from chromatic aberration. Furthermore, the images may serve as a stimulus for the hyperopic eye to relax some (if any) accommodation, especially in the absence of chromatic aberration. On the contrary, holographic myopic targets are also generated in front of the distance-corrected eye, and may serve as an accommodative stimulus for which myopic subjects tend to respond and accommodate more than hyperopic subjects.

Although one possible explanation for the difference in PBL between the two groups could be the difference in tolerance to blur when looking at large targets, this does not seem reasonable in this case. In the past, other researchers have also observed a difference between the vision of myopic subjects and non-myopic subjects, often with the former having better vision (George & Rosenfield, 2004; Poulere, Moschandreas, Kontadakis, Pallikaris, & Plainis, 2013; Rosenfield, Hong, & George, 2004; Wang, Ciuffreda, & Vasudevan, 2006) possibly through some neural adaptation process. However, if the vision of the myopic group was better, one would expect a higher PBL, rather than a reduced PBL as observed in this study. Therefore, the difference in the level of vision between the myopic and non-myopic subjects may not explain the results observed in this experiment.

Conclusions

5.7

Myopic subjects were found to have a lower PBL than hyperopic subjects in recognising large characters that were presented through a hologram. Some emmetropic subjects responded like myopic subjects and other emmetropic subjects responded like hyperopic subjects. These differences were not observed when a comparable study was conducted with a standard test chart under white light illumination. The two studies differed in the illumination (laser coherent light vs. white incoherent light) used and the manner in which the blur was introduced (multi-vergence target in a hologram vs. positive lenses to blur a distant test chart).

The results on the PBL of hyperopic and myopic subjects obtained with the hologram seem to indicate the possibility of the MVT hologram triggering some accommodation in myopic subjects, and subsequently resulting in them experiencing a reduced mean PBL compared to hyperopic subjects. This effect was also observed in a previous independent study using a different MVT hologram (Chapter 4).

Chapter 6 Holography and accommodation — role of a Mandelbaum-like Effect in the differentiation of hyperopia and myopia using a hologram

This chapter has been published as follows:

Nguyen, N., Avudainayagam, C. S., & Avudainayagam, K. V. (2013). Role of Mandelbaum-like effect in the differentiation of hyperopes and myopes using a hologram. *J Biomed Opt, 18*(8), 85001.

Part of this chapter has been presented as:

N. Nguyen, C. S. A., and K. V. Avudainayagam. (2009). *Holographic target probes the vision of myopes and hyperopes.* Paper presented at the Clinical Experimental Optometry, Auckland. Please see Appendix B for an abstract.

Part of this chapter was accepted for a poster at the Frontier in Optics Conference
N. Nguyen, C. S. A., and K. V. Avudainayagam (did not attend). *Holographic LogMAR Chart at Infinity to Test Vision*
Please see Appendix B for the abstract and paper.

Analysing the data obtained so far has given me insight into the place that these holograms will have in the future of refraction and accommodation measurements. Hologram for vision testing is a novel technique and takes some time to understand the observations relative to what has been found in the literature.

Up to this point, the following were observed about vision in a hologram:

1) Using a holographic logMAR (single focus) chart, some younger subjects were having trouble accommodating with a -0.25 D negative lens to bring the holographic logMAR chart into focus (Chapter 3).

2) Using two holographic MVTs to test for hyperopia and myopia individually, subjects had a slight lead of accommodation when trying to measure the refractive error. This lead was greater in myopic subjects than in hyperopic subjects (Chapter 4).

   Subjects also had trouble accommodating to see closer targets of the MVT hologram, resulting in the reduction of the amplitude of accommodation when measured using the MVT hologram. The effect was apparent for both younger and older subjects.

3) Using a single holographic MVT (consisting of integers) that is capable of measuring both myopic and hyperopic subjects, myopic subjects were found to have a reduced mean blur limit compared to hyperopic subjects. This was not observed when using white incoherent illumination.

In this chapter, the methodology was improved by using randomised letters (rather than reverse-sequential numbers) and repeated my experiment to see if previous results were repeatable. Also, a logMAR hologram was used to investigate if a difference in blur limits between refractive groups were also observable.

Introduction

6.1

In Chapter 5, the author reported an investigation of the vision of spectacle-corrected hyperopic and myopic subjects viewing numbers of angular size 50′ in a hologram which was recorded using a multi-vergence target (Nguyen, 2012). In viewing through this hologram (which is illuminated with light from a He-Ne laser), subjects see an array of positive and negative numbers placed at various distances from the eye. The negative numbers are seen in front of the eye as real objects and the positive numbers relate to virtual objects behind the eye. When the focusing error of a subject viewing through the hologram is corrected, he/she will see the number zero (which corresponds to a vergence of zero dioptres) clearly. The negative numbers will be seen clearly if the subject accommodates. However, positive numbers which correspond to positive vergences at the eye will appear blurred as one cannot exercise negative accommodation. When tested for the most positive blurred number recognised by corrected subjects, hyperopic subjects were found to differ from myopic subjects. Hyperopic subjects could recognise numbers with 0.9 D more of positive blur than myopic subjects. The most positive blur with which a subject could recognise a number was defined as the PBL of the subject in this study. There was no difference in the PBL when distance-corrected subjects viewed 50′ characters at 6 m distance under white light illumination with positive lenses to blur at the eye in a refractor. The observed difference in the PBL that was obtained with the multi-vergence hologram was then attributed to the multi-vergence nature of the target viewed through the hologram and/or the monochromaticity of the illumination used to view the hologram. To determine the role played by the multi-vergence target viewed through the hologram in the observed difference between hyperopic and myopic subjects, the author repeated the experiment with the multi-vergence hologram and conducted a second experiment in which subjects were tested with a hologram that contained the record of a logMAR chart at a single distance of infinity. Providing the logMAR chart at infinity in a hologram ensured that the illumination and viewing conditions remained the same as in my previous experiment with the multi-vergence hologram. Positive blur was introduced with lenses while subjects viewed through the logMAR hologram. The smallest line of letters recognised by the subjects was used to measure the vision of the subjects in logMAR units. Results from this experiment showed no difference in the vision of hyperopic and myopic subjects. In this paper, the author describes the experiments and the results obtained.

The research aims were to confirm the involuntary accommodation of myopic subjects to a holographic MVT and to determine whether an involuntary accommodation also manifested in a logMAR hologram. The hypotheses were that poor monochromatic illumination used in the MVT induced an involuntary accommodation in myopes. It was speculated that the monochromatic illumination used to reconstruct the logMAR hologram would also induce an involuntary accommodation in some subjects.

6.2

Experiment 1 (testing with an MVT hologram)

6.2.1 Subject recruitment and subjective refraction

Subjective refraction was performed to work out the spectacle correction required for subsequent holographic measurements. Subject recruitment and subjective refraction followed the same procedure and protocols as applied in Section 2.9.

6.2.2 The hologram of a multi-vergence target

A multi-vergence target was recorded into a hologram following the method described in Chapter 2.

In this study, 16 wooden rods were used to make the 3-D target for Experiment 1 and the vergence of the images seen through the hologram was designed to be in the range of -1 D to +6.5 D in steps of 0.5 D. Actual vergence and labelled used could be seen from Table **6.1**.

Table 6.1. Randomised letter label with the corresponding vergence.

Label	Vergence
O	-1.04
Z	-0.60
V	-0.06
Y	0.46
U	0.88
H	1.38
C	1.95
F	2.32
P	2.79
D	3.45
X	3.94
R	4.62
N	4.95
K	5.48
E	6.02
A	6.70

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Figure 6.1. Actual position of characters in the MVT.

6.2.3 Measurements with the multi-vergence hologram

Ten myopic subjects, nine emmetropic subjects, and 11 hyperopic subjects were included in this study. The mean spherical refractive error for the myopic subjects was in the range of -0.375 D to -5.5 D. Subjects with a mean spherical refractive error in the range of -0.25 D to +0.25 D were considered as emmetropic subjects. The mean spherical refractive error for the hyperopic subjects was in the range of +0.375 D to

+1.75 D. The subjects included in the study had little (0.25 D) or no astigmatism. During the experiment, subjects were tested at random. The experimenter provided the correction for the subject’s spherical refractive error, but did not know the actual vergences of the letters being called out. These things were done to reduce practitioner bias as an influence on the results. Ethics approval was obtained from the UNSW Human Research Ethics Committee. The spectacle correction for the subject was determined by subjective refraction using a refractor. The maximum plus lens for best visual acuity was the criterion for the subjective end point. The best corrected visual acuity was 6/7.5 or greater and the subjects had no significant pathology. For all the subjects, the right eye was occluded and the left eye was tested in the mesopic illumination of the clinic room.

Distance (spectacle)-corrected subjects were asked to view through the hologram as shown in Figure 2.6. When looking through the hologram with the distance-correction in place, positive characters arrive at the eye with converging wavefronts. These letters are therefore seen with positive blur. The subject was asked to call out all of the letters that they could recognise. The letter with the most positive blur that is recognised by the subject is recorded. The vergence corresponding to this letter was used to obtain the PBL (also called the limiting blur) of the subject for the recognition of the 50’ character viewed through the hologram.

Autorefraction, conventional refraction, and holographic measurements were all performed sequentially (in that order) in one session by one sole practitioner under the same room conditions.

6.2.4 Results with the multi-vergence hologram

The data obtained with the multi-vergence hologram for all the subjects in Experiment 1 are shown in Table 6.2, 6.3 and 6.4.

Table 6.2. The data obtained for the myopic subjects measured with the MVT hologram.

Subject number	Mean sphere of the spectacle correction	Age (years)	Pupil size (mm)	PBL (Dioptre)
1	-5.5	23	6.7	0.46
2	-5.25	23	6	0
3	-3.75	21	5.8	1.95
4	-3.375	26	5	0.59
5	-1.75	17	5.5	0.46
6	-1.625	13	5	2.45
7	-1.375	40	5.9	0.07
8	-0.5	48	3	1.95
9	-0.375	29	6.1	2.44
10	-0.375	36	5	0.07
Mean	-2.4	28	5.4	1.04

Table 6.3. The data obtained for the emmetropic subjects measured with the MVT hologram.

Subject number	Mean sphere of the spectacle correction	Age (years)	Pupil size (mm)	PBL (Dioptre)
11	-0.25	20	4.0	0.88
12	-0.25	36	5.8	0.88
13	-0.125	36	6.3	1.01
14	-0.125	46	4.6	1.01
15	0.00	28	4.5	1.95
16	0.00	51	6.6	1.95
17	0.00	9	5.0	2.32
18	0.00	46	4.0	1.95
19	0.25	42	4.7	1.95
Mean	-0.06	35	5.1	1.54

Table 6.4. The data obtained for the hyperopic subjects measured with the MVT hologram.

Subject number	Mean sphere of the spectacle correction	Age (years)	Pupil size (mm)	PBL (Dioptre)
20	0.375	51	6.5	1.51
21	0.75	42	5.3	1.95
22	0.75	47	5.0	2.32
23	0.75	47	3.8	1.95
24	0.75	48	3.5	1.95
25	0.75	19	4.0	1.95
26	1.25	51	5.0	0.46
27	1.375	58	5.1	2.08
28	1.625	55	5.0	2.32
29	1.75	55	5.0	2.32
30	1.75	47	5.0	1.95
Mean	1.08	47	4.83	1.89

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Figure 6.2. PBL (limiting blur) for all of the subjects seeing through the hologram of the multi-vergence target.

Figure 6.2 shows the PBL for all the subjects vs. the subject number. The subject number was ordered according to the refractive error. Subject number 1 was the most myopic subject (on the left extreme of the *x*-axis) and subject number 30 was the most hyperopic subject (on the right extreme of the *x*-axis). Dashed vertical lines demarcate the refractive error groups. The horizontal dashed lines represent the mean values of the PBL that were obtained for each group. The mean PBL for myopic subjects was 1.04 D with a standard deviation of 1.03 D, while for hyperopic subjects it was 1.89 D with a standard deviation of 0.53 D. Thus, the mean PBL for hyperopic subjects was 0.85 D greater than that for myopic subjects, and this was statistically significant ($P = 0.02$ for unequal variances). The differences in the limit of positive blur with which distance-corrected hyperopic subjects and distance-corrected myopic subjects recognised the large high contrast letters viewed through the hologram were consistent with the results that were obtained from a larger group with a wider range of ages and refractive errors in my earlier investigation (Chapter 5). As reported in this earlier investigation, some emmetropic subjects responded like myopic subjects while others responded like hyperopic subjects. The mean PBL for emmetropic subjects was 1.54 D (standard deviation of 0.34 D). The difference between the mean PBL of emmetropic subjects and hyperopic subjects and the difference between the mean PBL of emmetropic and myopic subjects were not statistically significant. The *P*-value for the difference in the mean PBL of emmetropic and myopic subjects was 0.2, and the *P*-value for emmetropic and hyperopic subjects was 0.19. As before (Chapter 5) there was a poor correlation between the age and the PBL, as well as between the pupil size and the PBL for all subjects. The Pearson Correlation Coefficient, r, in this study was 0.21 ($P = 0.13$) for the association between age and the PBL, and −0.3 ($P = 0.054$) for the association between pupil size and the PBL.

6.2.5 Effect of cycloplegia

To investigate the role of accommodation on the results obtained with the multi-vergence hologram, nine myopic, two emmetropic and four hyperopic eyes were tested under cycloplegia. One drop of cyclopentolate hydrochloride 1% was administered in the eye to be tested, with temporary punctual occlusion to minimise systemic absorption. One drop has been found to be effective for cycloplegic refraction whilst minimising possible adverse effects (Bagheri, Givrad, Yazdani, & Reza Mohebbi, 2007; Hug & Olitsky, 2007). The pupil was checked after 40 minutes and all subjects showed reasonably dilated pupils of greater than 6 mm. This check was done to ensure that the cycloplegic agent was having an effect on the eye. If pupil size was not reasonably dilated, a reading chart would be used to confirm cycloplegia of the eye. An extra drop of cyclopentolate hydrochloride 1% could then be instilled into the eye if the first drop was inadequate. The refractive error of the eye under cycloplegia was then measured by subjective refraction using the criterion of maximum plus lens for best visual acuity.

The cycloplegic eye was provided with the mean sphere of the distance-correction, and the PBL for the eye was measured using the multi-vergence hologram, with the fellow eye occluded. The data obtained on the PBL under cycloplegia for the tested eyes are shown in Tables 6.5, 6.6 and 6.7. Figure 6.3 shows the PBL for all the eyes tested under cycloplegia. The mean PBL obtained for myopic subjects was 0.85 D with a standard deviation of 0.09 D, and for hyperopic subjects it was 0.95 D with a standard deviation of 0.50 D. The difference of 0.1 D in the mean PBL was not statistically significant ($P = 0.7$ for unequal variances). Variations in the PBL under cycloplegia for the hyperopic eyes tested appeared to be due to an effect of pupil size.

Figure 6.3. PBL obtained under cycloplegia.

Table 6.5. The data obtained with the multi-vergence hologram for the myopic eyes under cycloplegia.

Subject number	Mean sphere of the spectacle correction	Age (years)	Pupil Size (mm)	PBL (Dioptre)
1	-1.25	18	8	0.88
2	-1.25	18	8	0.88
3	-1.50	19	7	0.88
4	-4.125	22	7	0.59
5	-3.00	20	7	0.88
6	-2.50	18	8	0.88
7	-3.00	18	8	0.88
8	-1.50	19	8	0.88
9	-1.50	19	8	0.88
Mean	-2.18	19	7.67	0.85

Table 6.6. The data obtained with the multi-vergence hologram for the emmetropic eyes under cycloplegia.

Subject number	Mean sphere of the spectacle correction (Dioptre)	Age (years)	Pupil size (mm)	PBL (Dioptre)
10	-0.125	50	6	1.01
11	-0.125	50	6	1.01
Mean	-0.125	50	6	1.01

Table 6.7. The data obtained with the multi-vergence hologram for the hyperopic eyes under cycloplegia.

Subject number	Mean sphere of the spectacle correction (Dioptre)	Age (years)	Pupil size (mm)	PBL (Dioptre)
12	+2.50	59	6	1.38
13	+2.25	68	5	1.38
14	+0.38	9	7	0.59
15	+0.50	9	7	0.46
Mean	+1.41	36.25	6.25	0.95

While there was hardly any difference in the PBL for all subjects under cycloplegia, the value of the PBL for all subjects was close to 1 D under cycloplegia as against the 2 D of PBL that was obtained in white light for all of the subjects in the earlier investigation (Chapter 5). This can be attributed to the reduced depth of focus and the effects of aberrations arising from the larger pupil size under cycloplegia. In Experiment 1, the average pupil size of all the subjects was 5.1 mm without cycloplegia and it was 7.1 mm in the investigation under cycloplegia.

Experiment 2 (testing with a logMAR hologram)

6.3

6.3.1 Subject recruitment and subjective refraction

Subjective refraction was performed to work out the spectacle correction required for subsequent holographic measurements. Subject recruitment and subjective refraction followed the same procedure and protocols as applied in Sections 2.9 and 3.2.3 respectively.

6.3.2 The hologram of a logMAR chart at infinity

Figure 3.1 shows the arrangement to record the logMAR hologram. A logMAR chart for a testing distance of 50 cm was used as the target in recording the hologram. The chart was illuminated with light from a He-Ne laser and imaged at infinity using a 2 D lens, which had a focal length of 50 cm. A hologram of the image-forming wavefront emerging from the lens was recorded by interference with a path-matched plane reference wave derived from the same laser (as shown in Figure 3.1). The recorded hologram was developed and bleached to obtain the phase hologram of the logMAR chart at infinity.

6.3.3 Measurements with the logMAR hologram

To measure various subjects using the logMAR hologram, the subject placed their eye close to the hologram, and the hologram was illuminated as described in Experiment 1. The subject then saw the image of the logMAR chart at infinity. As plane waves reached the eye of the subject from the logMAR hologram, the position of the subject's eye behind the hologram was not critical in this experiment.

Subjects were asked to view through the logMAR hologram with a +2 D lens placed over the mean sphere of their spectacle correction. The smallest letters recognised in the logMAR chart seen through the hologram were used to measure their vision in the presence of +2 D blur. The measurements were then repeated with a +1 D lens to blur. The visual acuity of the subjects without any lens to blur their vision was also measured using the logMAR hologram.

Fourteen myopic subjects, 17 emmetropic subjects, and 11 hyperopic subjects participated in this study. The subjects included in the study had little (0.25 D) or no astigmatism. The mean spherical refractive error for the myopic subjects was in the range of -0.5 D to -4.75 D. The mean spherical refractive error for the hyperopic subjects was in the range of +0.5 D to +2.875 D. Subjects with a mean spherical refractive error in the range of -0.25 D to +0.25 D were considered as emmetropic. As before, the spectacle correction for the subject was determined by subjective refraction using a refractor. The best corrected visual acuity was 6/7.5 or greater and the subjects had no significant pathology. For all of the subjects, the left eye was tested in the mesopic illumination of the clinic room.

Table 6.8. The data obtained for the myopic subjects measured with the logMAR hologram.

Subject numbers	Mean sphere of the spectacle correction	Age (years)	Pupil size (mm)	logMAR value with no lens to blur	logMAR value with 1 D lens	logMAR Value with +2 D
1	-4.75	38	5.5	0.46	0.96	≥ 1.10
2	-4	25	5.0	0.64	0.96	≥ 1.10
3	-3.375	23	5.5	0.80	0.94	≥ 1.10
4	-2.875	60	5.5	0.52	0.84	1.04
5	-2.75	24	5.0	0.58	0.96	≥ 1.10
6	-1.75	19	6.0	0.56	0.76	1.06
7	-1.125	39	6.5	0.50	0.80	0.96
8	-1.125	17	5.0	0.46	0.66	1.06
9	-1	48	4.0	0.54	0.94	1.06
10	-0.875	10	7.0	0.50	0.80	1.04
11	-0.875	13	6.5	0.40	0.86	≥ 1.10
12	-0.75	13	7.0	0.40	0.80	≥ 1.10
13	-0.625	17	6.5	0.50	0.82	1.08
14	-0.50	14	5.0	0.70	1.00	≥ 1.10
Mean	-1.90	26	5.7	0.54	0.86	-

Table 6.9. The data obtained for the emmetropic subjects measured with the logMAR hologram.

Subject number	Mean sphere of the spectacle correction (Dioptre)	Age (Years)	Pupil size (mm)	logMAR value with no lens to blur	logMAR value with 1 D lens to blur	logMAR value with 2 D lens to blur
15	-0.25	44	5.5	0.60	0.84	1.04
16	-0.25	78	5.0	0.40	0.86	1.08
17	-0.125	13	7.0	0.50	0.80	≥ 1.10
18	-0.125	42	4.5	0.52	0.82	≥ 1.10
19	-0.125	40	6.0	0.60	0.76	≥ 1.10
20	-0.125	57	6.5	0.64	1.00	≥ 1.10
21	0.00	42	4.5	0.40	0.82	≥ 1.10
22	0.00	19	6.0	0.64	0.94	≥ 1.10
23	0.00	19	6.5	0.50	1.00	≥ 1.10
24	0.00	25	6.0	0.60	0.84	≥ 1.10
25	0.00	18	6.0	0.50	0.80	≥ 1.10
26	0.00	9	5.5	0.36	0.86	1.04
27	0.00	49	4.5	0.48	0.84	1.08
28	0.25	42	4.5	0.50	0.80	≥ 1.10
29	0.25	42	4.5	0.50	0.88	≥ 1.10
30	0.25	14	5.0	0.76	1.00	≥ 1.10
Mean	0.00	35	5.4	0.53	0.87	-

Table 6.10. The data obtained for the hyperopic subjects measured with the logMAR hologram.

Subject number	Mean sphere of the spectacle correction (Dioptre)	Age (Years)	Pupil size (mm)	logMAR value with no lens to blur	logMAR value with 1 D lens to blur	logMAR value with 2 D lens to blur
32	0.5	41	4.5	0.58	0.96	1.08
33	0.5	31	4.0	0.60	0.96	1.04
34	0.625	39	6.0	0.78	1.06	≥ 1.10
35	0.75	48	6.0	0.46	0.80	1.06
36	0.75	9	5.0	0.80	1.06	≥ 1.10
37	0.75	49	4.0	0.40	0.66	0.86
38	0.875	42	4.5	0.52	0.80	1.08
39	1.125	43	4.0	0.42	0.86	1.06
40	1.375	43	4.0	0.60	0.74	≥ 1.10
41	1.5	53	5.0	0.32	0.70	1.00
42	2.875	52	5.5	0.58	0.94	≥ 1.10
Mean	1.1	41	4.8	0.55	0.87	-

6.3.4 Results obtained with the logMAR hologram

The data obtained using the logMAR holograms are shown in Tables 6.8, 6.9 and 6.10. The average age and the pupil size of the various refractive groups were fairly close across Experiments 1 and Experiment 2 (see Table 6.11).

Table 6.11. Average age and pupil size of subjects in Experiment 1 and Experiment 2

Refractive groups	Average age		Average pupil size	
	Experiment 1	Experiment 2	Experiment 1	Experiment 2
Myopia	28 ± 11	26 ± 15	5.4 ± 1	5.7 ± 0.9
Emmetropia	35 ± 14	35 ± 18	5.1 ± 1	5.4 ± 0.8
Hyperopia	47 ± 10	41 ± 12	4.8 ± 0.8	4.8 ± 0.8

The visual acuity for all of the subjects using the logMAR hologram with no lens to blur their vision has been plotted against the subject number in Figure 6.4.

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Figure 6.4. The logMAR values for all the subjects seeing through the hologram of the logMAR chart with no lens to blur.

The subject number was ordered according to the refractive error. The horizontal dashed lines correspond to mean values of the PBL for each group. The logMAR value of the mean vision of the subjects with no additional lens to blur their vision was around 0.55. There was no difference in the mean vision between the refractive groups. The difference in the mean vision of hyperopic and myopic subjects was 0.01 in logMAR units, with a *P*-value of 0.84.

With a +1 D lens to blur, the logMAR value of the mean vision for all the subjects were close to 0.86 logMAR, and there was no difference in the vision between the refractive error groups (Figure 6.5). With a +1 D lens to blur, the vision falls by about 0.3 logMAR for all refractive groups compared to the vision with no lens to blur. The difference in the mean vision of hyperopic and myopic subjects was 0.01 logMAR with a *P*-value of 0.95. The results with the logMAR hologram have been summarised in Table 6.12.

The topmost line of the logMAR chart in the hologram corresponds to a logMAR value of 1.0 and the angular size of the letters in this line is 50′. With a +2 D lens to blur, some of the subjects in each refractive group could read a few letters from this line, while others could not read any letters from this line. The logMAR value for the vision of the subjects who could not read any letter from this line was > 1.10. The response of myopic and hyperopic subjects was similar with a +2 D lens to blur (Tables 6.8 and 6.10).

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Figure 6.5. The logMAR values for all the subjects seeing through the hologram of the logMAR chart with +1 D blur.

Table 6.12. Summary of the results with the hologram of a logMAR chart at infinity.

	Vision through logMAR hologram (logMAR values)			
Refractive error	With no lens to blur		With +1 D blur	
	Mean	SD	Mean	SD
Myopia	0.54	0.11	0.86	0.10
Emmetropia	0.53	0.10	0.87	0.08
Hyperopia	0.55	0.15	0.87	0.14

Discussion

6.4

As in my earlier study (Chapter 5), results obtained from Experiment 1 indicate that when a multi-vergence target is presented through a hologram, distance-corrected hyperopic subjects recognise large characters with more positive blur (0.85 D) than distance-corrected myopic subjects. The maximum positive blur under which a fixed-size character is recognised through the multi-vergence hologram was used to compare the vision of hyperopic and myopic subjects in this Experiment.

In Experiment 2, when the blur was introduced with a positive lens to distance-corrected subjects viewing a logMAR chart at a single distance of infinity in a hologram, there was no difference in the vision between hyperopic and myopic subjects. Subjects' vision was compared using the logMAR values corresponding to the smallest size character that can be recognised in the logMAR hologram. A +1 D blur related to a readability of three lines in the logMAR hologram (0.3 in logMAR units).

In both experiments, subjects viewed through a hologram which was illuminated by a plane reference wave from a He-Ne laser (633 nm). However, a difference in the vision of hyperopic and myopic subjects was obtained in Experiment 1, whereas no difference was seen in the vision of hyperopic and myopic subjects in Experiment 2. In Experiment 2, a similar number of myopic and hyperopic subjects could recognise large characters with +2 D blur, but this was not the case in Experiment 1. As the logMAR hologram provides a target at a single distance of infinity and the multi-vergence hologram provides targets at various distances from the eye, the observed difference in the vision between hyperopic and myopic subjects in Experiment 1 may be due to an effect similar to that of the Mandelbaum Effect (Mandelbaum, 1960).

In the Mandelbaum Effect, subjects attempting to view a distant target through an intermediate intervening screen fail to focus on the distant target. Instead, subjects find themselves focusing involuntarily on the screen. The distance at which this occurs varies for different subjects. When presented with a pair of stimuli separated by 2 D at various distances from the eye, a researcher found that the subjects had a tendency to involuntarily focus on the target that is closer to the location of the dark focus of the subject, indicating that the Mandelbaum Effect is due to a response bias of the accommodative system (Owens, 1979). The dark focus of accommodation is also addressed in the literature as the resting state of accommodation or tonic accommodation (Maddock, Millodot, Leat, & Johnson, 1981; McBrien & Millodot, 1987; Miwa & Tokoro, 1993; Rosner & Rosner, 1989).

In the current study with the multi-vergence hologram, the vergence range of the images seen through the hologram was between -1 D to +6.5 D in steps of 0.5 D. Distance-corrected myopic subjects were able to recognise large characters, with only up to +1 D of blur in the hologram of this multi-vergence target. This was not the case, however, with the distance-corrected hyperopic subjects, who were able to recognise characters having up to +2 D of blur in the multi-vergence hologram. When presented with a distant test chart in white light, both of these groups were able to recognise large characters with around +2 D of blur (Chapter 5).

Consequently, it appears that the presence of the target with -1 D vergence in the multi-vergence hologram is influencing the myopic group to recognise characters having only up to +1 D of vergence in the multi-vergence hologram. Maybe myopic subjects do have 2 D of mean PBL similarly to hyperopic subjects, but myopic subjects are involuntarily accommodating onto the -1 D target, resulting in a lower measured mean PBL of about +1 D. This was in contrast to the situation for distance-corrected hyperopic subjects, in which it was speculated that their refractive state was neutral and that their focus was on the 0 D target, permitting the MVT hologram to measure up to + 2 D of PBL. Essentially, it appears that an effect similar to the Mandelbaum Effect manifested in the vision of some subjects. When presented with a multi-vergence target in a hologram that provides stimuli at various distances, myopic subjects tended to focus on the near stimulus (character at 1 m distance from the eye) and hyperopic subjects tended to focus on the distant stimulus (character at infinity). Perhaps distance-corrected myopic subjects are drawn by the Mandelbaum-like Effect to focus on the character with -1 D vergence, which would be close to their resting state of accommodation. The possibility for this involuntary accommodation in the MVT hologram is different to the usual accommodation people exert to focus on near objects. Instead, involuntary accommodation is often experienced by some individuals during certain stimulus conditions and would make distance objects fuzzy (individuals becoming more myopic). Conditions that might stimulate an involuntary accommodation in individuals could be from poor illumination (night myopia), lack of stimulus detail (empty field myopia), and conflicting objects (Mandelbaum effect) (Rabbetts, 2007). This study showed that the MVT hologram may be a distinctly different condition where involuntary accommodation is also triggered in some individuals. The MVT hologram is distinctly different because it does not belong to any particular classification for involuntary accommodation towards the dark focus. The situation is similar to night myopia since the monochromatic illumination used in the hologram is also dim. However, characters observed are still high-contrast and easily recognisable and so should not elicit an involuntary accommodation. The laser speckles observed by the subject in the hologram are high contrast, uniformly distributed and are always in focus irrespective of the individual's refractive state. This effect is similar to empty field myopia where vision is unchanged irrespective of the individual's refractive state. Unlike the Mandelbaum effect where there are superimposed and conflicting stimuli, the MVT consists of numerous stimuli that are only in close proximity to each other in a 4x4 array. Although not superimposed, adjacent stimuli are adequate to elicit an involuntary accommodation in some subjects.

Although the resting state of accommodation of hyperopic subjects is known to be larger than that of myopic subjects (McBrien & Millodot, 1987; Rosner & Rosner, 1989), distance-corrected hyperopic subjects tend to focus on the character with 0 D vergence in viewing through the multi-vergence hologram. This suggests that the vision of hyperopic subjects is influenced by their latent hyperopia in viewing through the multi-vergence target.

This Mandelbaum-like effect was observed in my earlier study too, with the multi-vergence target in a hologram having numbers as targets in the vergence range of -5 D to +2.5 D (Avudainayagam et al., 2007). In trying to measure the amplitude of accommodation of university-age subjects using the multi-vergence hologram, it was found that distance-corrected subjects could not accommodate to see some of the closer numbers that were well within the range of their clear vision, in spite of exercising their will. When presented with the stimulus of a near letter chart in white light close behind the hologram (at 40 cm from the subject's eye), the accommodation of the subjects was triggered and they were able to read these numbers. It was very striking that without the near stimulus, the young subjects could not recognise numbers of angular size around 50′ projected within their normal range of clear vision (at 20–25 cm from the eye). There is some debate in the literature regarding the existence and explanation of the Mandelbaum Effect (Rosenfield & Ciuffreda, 1991; Stark & Atchison, 1998). My observations with the multi-vergence hologram are consistent with Owen's findings described earlier in this section (Owens, 1979), and suggest that the Mandelbaum Effect exists and manifests itself strongly under certain viewing conditions.

It is known that phenomena such as night myopia, empty field myopia, and instrument myopia correlate highly in magnitude with the dark focus (Leibowitz & Owens, 1975). It would be interesting to measure the dark focus of individual subjects and see how it relates to their PBL.

The hologram of a multi-vergence target with an extended negative and positive vergence range can be used to measure the refractive state of the eye (Avudainayagam et al., 2007). In this measurement, an uncorrected eye viewing a distant fixation target in white light is presented briefly (in flashes of about one second duration) with the multi-vergence hologram, and the most positive character seen clearly by the subject gives a measure of their refractive error (Avudainayagam et al., 2007). When a spectacle-corrected eye is presented with such a multi-vergence hologram in total darkness, the author believes that the clearest character seen would give a measure of the eye’s dark focus.

Looking more closely at the results of Experiment 2 with the logMAR hologram, a mean vision of 0.55 logMAR for the distance-corrected subjects is much worse than the visual acuity that is obtained under white light illumination. The reduced visual acuity may be attributed to the coherent nature of the laser light illuminating the hologram (Artigas & Felipe, 1988). The range of the measured values of the visual acuity with the logMAR hologram is 0.48 in logMAR units. As I recruited subjects with vision better than 6/6 in white light, the expected range for the spread in the visual acuity was about 0.4 logMAR units (between 6/3 and 6/7.5 i.e. -0.3 logMAR to +0.1 logMAR). It is possible that instrument myopia may have worsened the results. However, if instrument myopia played a role in measuring vision using the logMAR hologram, the measured vision of all the subjects would be correlated with their ages, as instrument myopia is an accommodation-related phenomenon. However, the Pearson Correlation Coefficient r between the age and the logMAR value of the vision for all the subjects was small ($r = -0.23$, $P = 0.07$, see Table 6). There was no correlation between the age and the logMAR value of the vision for myopic subjects ($r = 0.01$, $P = 0.97$), while the correlation between the age and the logMAR value of the vision for hyperopic subjects was strong ($r = -0.73$, $P = 0.005$). The negative sign for r obtained for hyperopic subjects implies that younger hyperopic subjects had a poorer vision in viewing through the logMAR hologram with their distance-correction than older hyperopic subjects. It is known that when a distance-correction is provided to hyperopic subjects, some latent accommodation remains in play. As the distance-corrected vision through the logMAR hologram was worse for younger hyperopic subjects than that for older hyperopic subjects, this seems to suggest that the latent hyperopia is in play when hyperopic subjects view through the logMAR hologram. This is consistent with my initial findings reported in an earlier paper (Avudainayagam et al., 2007), which suggested that it may be possible to get a measure of hyperopia without the intervention of latent accommodation using the multi-vergence hologram.

Under incoherent light, mesopic vision varies considerably and could range from being unaffected at higher chart luminances (such 7.5 cd/m^2) to vision worse by 0.5 logMAR at low chart luminances of 0.075 cd/m^2 (Johnson & Casson, 1995). However, vision under incoherent illumination may not be the same when the optical system is illuminated by coherent light. Holograms are reconstructed using coherent illumination, and the spatial cut-off frequency for any optical system illuminated by coherent light is drastically reduced because of the presence of laser speckle (Goodman, 1969). The eye is no exception and speckle reduces both contrast sensitivity and visual acuity in human subjects (Artigas, Buades, & Felipe, 1994; Artigas & Felipe, 1988). Under coherent lighting, Artigas & Felipe (1988) only noted a 40% drop in visual acuity in their experiment, with poorer vision as the chart luminance increases. This is counter-intuitive and is opposite to visual acuity measurements done under incoherent illumination. Little is known about visual acuity in a hologram, but perhaps the poorer than expected vision (70% drop) could be from a combination of different chart luminance, the monochromatic and coherent nature of the illumination, as well as the interference of laser speckle.

Another possible explanation for the poor visual acuity measurement observed in the hologram is the fact that the spectral sensitivity of the eye at this wavelength of light is relatively poor. This could be easily tested by using a green laser to record future holograms since the eye has peak sensitivity around this region of light.

The negative correlation between pupil size and logMAR value (vision) is quite interesting. A moderate level of negative correlation (r = -0.45, P = 0.05) between the pupil size and the logMAR value for myopic subjects implies that vision improves as the pupil size increases. This correlation in myopic subjects did reach statistical significance. Vision generally improves (as indicated by a lower logMAR visual acuity) because of greater depth of focus (smaller blur circles on the retina). However, in a coherent optical system, laser speckle also plays a role. It is well accepted that reducing the pupil size increases the size of the laser speckle, consequently resulting in poorer vision (i.e. higher logMAR VA). In this myopic group, smaller pupil sizes resulted in poorer vision, which suggests that maybe the coherent nature of the light source played a stronger role in reducing the visual acuity of myopic subjects. For hyperopic subjects, a low positive correlation existed between the pupil size and the logMAR (r =0.29, P = 0.19). There was not enough evidence to reject the null hypothesis (that there was no correlation between the two variables). This suggests that the vision of hyperopic subjects was probably less affected by the coherent light source. However, more subjects will need to be tested to verify this hypothesis because the correlation did not reach statistical significance.

Fig 6.2 is a plot showing the PBL of the three refractive groups. From this plot, one can visually observe that the mean PBL for myopic was lower whereas the mean PBL for hyperopic subjects was higher. Interestingly, the mean PBL for the emmetropic group was located somewhat in between. This trend was also observed from a previous study using different subjects (Figures 5.2). From Figures 5.2 and 6.2, it could be observed that some emmetropic subjects were behaving like the hyperopic group while some others were behaving like the myopic group. Since the refractive error of emmetropic people could change to become either myopic or hyperopic. It was wondered whether the emmetropic subjects that responded similarly to the myopic group would eventually develop myopia. On a similar line of thought, it was wondered if emmetropic subjects that responded like the hyperopic group (when viewing the MVT hologram) would have a stable refractive error (and remain non-myopic). It is unknown why myopic subjects behaved any differently to hyperopic subjects, but myopic progression may be a possible factor. Are the myopic subjects that are behaving so differently (to hyperopic subjects) in the MVT hologram more susceptible to myopic progression? Future studies might investigate any association between reduced PBL and myopic progression. When using the logMAR hologram to test for vision, there were no differences between refractive groups, as well as little correlation between age and vision. The single vergence of the logMAR hologram is unable to elicit an involuntary accommodation in subjects. This suggests that the multi-vergence nature of the stimuli is important to bring out IA.

With the use of a cycloplegic agent, the difference between the refractive groups were both clinical and statistically insignificant (0.1 D, p = 0.70). Since a difference between the two groups was observed before the use of the cycloplegic agent, and this difference disappeared after its use. This confirms that the cause for the difference between myopic and hyperopic subjects is accommodative in nature.

When testing for spherical refractive error, subjects did not wear their spectacles. The MVT hologram could locate the far-point of the subject since objects placed at the far-point would be clear. To measure the PBL of the subject, a single hologram was used and the subject was distance-corrected with a trial lens. Using this setup, one would expect all subjects with similar vision to have similar PBLs. However, some subjects were involuntarily accommodating down the MVT hologram, and scored a lower PBL than usual (results of Chapters 5 and 6). When a cycloplegic agent was used to impair accommodation, all subjects had a similar level of PBL (Chapter 6). It is therefore reasonable to conclude that the difference in PBL observed is from the involuntary accommodation of some subjects.

Table 6.13. The Pearson Correlation Coefficient between the age and vision, and the pupil size and vision for distance-corrected subjects viewing through the logMAR hologram.

Refractive groups	Pearson Correlation Coefficient *r* between age and logMAR value	Pearson Correlation Coefficient *r* between pupil size and vision
Myopia	0.01 (*P* = 0.97)	-0.45 (*P* = 0.05)
Emmetropia	-0.18 (*P* = 0.24)	0.24 (*P* = 0.18)
Hyperopia	-0.73 (*P* = 0.005)	0.29 (*P* = 0.19)
All subjects	-0.23 (*P* = 0.07)	-0.002 (*P* = 0.99)

Table 6.13 also lists the Pearson Correlation Coefficient between the pupil size and the logMAR value for various refractive groups. A moderate level of negative correlation (*r* = -0.45, *P* = 0.05) between the pupil size and the logMAR value for myopic subjects implies that vision improves as the pupil size increases. Vision generally improves (as indicated by a lower logMAR visual acuity) because of greater depth of focus (smaller blur circles on the retina); however, in a coherent optical system, laser speckle also plays a role. It is well accepted that reducing the pupil size increases the size of the laser speckle, consequently resulting in poorer vision (i.e. higher logMAR visual acuity). In this myopic group, smaller pupil sizes resulted in poorer vision, which suggests that maybe the coherent nature of the light source played a stronger role. In other words, for some unknown reason, myopic subjects are affected by the coherent nature of the laser light, resulting in an involuntary accommodation towards the nearer targets (and this was measured in the MVT hologram as a lower mean PBL value in this study).

On the contrary, a medium level positive correlation between the pupil size and the logMAR value for hyperopic subjects (*r* =0.29, *P* = 0.19) implies that vision increases with a decrease in pupil size (and larger laser speckle). This suggests that hyperopic subjects are less affected by the laser light, so they would accommodate accurately onto the zero vergence target, resulting in a ‘normal’ mean PBL of ~+2 D.

It is possible to artificially reduce the pupil size during hologram recording, from the standard 8 mm currently utilised to a smaller value such as 3.5 mm. In a dark room, the artificial pupil of 3.5 mm will ensure that laser speckle is affecting all subjects similarly. The results of this study suggest that myopic subjects have worse vision with reduced pupil size (and that hyperopic subjects have better vision with reduced pupil size); thus, it is expected that this will bring out a difference in vision between the two refractive groups when measured with a logMAR hologram.

It is unknown why myopic subjects behaved any differently to hyperopic subjects, but myopic progression may be a possible factor. Are the myopic subjects that are behaving so differently (to hyperopic subjects) in the hologram more susceptible to myopic progression? Future studies might investigate any association between reduced PBL and myopic progression.

In the current study, the same set of subjects took part in both the tests. However, the number of hyperopic subjects included in this study was small and the level of hyperopia was low. This resulted in a mean difference of 0.62 D in the PBL, which was statistically significant with a *P*-value of 0.027. Furthermore, the pupil size for all the subjects was measured on the fellow eye using the digital pupillometer from NeurOptics (Model 59001). The Pearson Correlation Coefficient between the pupil size and the PBL for all the subjects was found to be −0.19. Thus, the observed difference was not an effect of pupil size. No difference in the PBL between the refractive groups was obtained in white light. The mean PBL was again about 1.90 D for all refractive groups in white light.

Conclusions

6.5

The results of the experiments described in this paper suggest that when distance-corrected myopic and hyperopic subjects are presented with a multi-vergence target in a hologram that contains images with negative and positive vergences, an effect similar to the Mandelbaum Effect, influences the vision of the subjects. The results from the current study show that there is no difference in the mean logMAR values of the vision of various refractive groups when tested with a logMAR chart at infinity in a hologram.

An upshot from this study is the logMAR chart at infinity recorded in a hologram. With further experimentation and using larger characters, it may be possible to standardise and calibrate the logMAR hologram to measure the visual acuity of myopic subjects and to predict/estimate the latent hyperopia of hyperopic subjects. It could be made compact, portable, and inexpensive by using a laser diode for illumination.

The MVT hologram is able to measure the current refractive state of the eye. In total darkness, it may be possible to use the MVT hologram to measurement the dark focus of the eye.

Chapter 7 Involuntary accommodation in a non-holographic multi-vergence target

7.1 Introduction

The Mandelbaum Effect, first described in 1960, refers to the involuntary accommodation of the eye to an intermediate distance (dark focus) due to degradation to the visual stimulus (Mandelbaum, 1960; Owens, 1979). The effect varies between individuals significantly, and can range from -0.25 D to 4.00 D, but tends to average at 1.50 D (Leibowitz & Owens, 1978).

A Mandelbaum-like Effect (MLE) was previously observed in myopic subjects when the vision of myopic and hyperopic subjects was measured using a multi-vergence target (MVT) under monochromatic 633 nm 'red' light in a hologram (Chapters 5 and 6). Here, myopic subjects were found to be involuntarily accommodating by about 1 D relative to hyperopic subjects in the presence of an MVT, an effect similar to the Mandelbaum Effect.

The MVT consisted of both diverging image wavefronts (myopic targets) and converging image wavefronts (hyperopic targets). By measuring the limit of the converging wavefronts where character recognition was just possible, it gives a measure of the PBL for letter recognition (PBL) of the subject. Previous chapters have used the term 'PBL' to describe this parameter. The average PBL for myopic subjects under holography was lower than that for hyperopic subjects. It was hypothesised that the myopic targets of the holographic MVT were closer or nearer to the subject, and were responsible for the involuntary accommodation in myopic subjects, resulting in a lower PBL response. This involuntary accommodation resulted in a reduced PBL response, an effect described as the Mandelbaum-like Effect (MLE) in previous research (Chapter 6).

A simple optometer using the MVT with red laser diode illumination would create an MVT that is similar to a holographic MVT. The exception to the similarity is that a holographic image is formed through the phase-conjugated reconstruction from diffractive effects to reveal a pseudo-stereoscopic image, whereas the optometer's multi-vergence image has true-stereopsis from refraction with a +20 D lens.

The aim of this study was to investigate whether a non-holographic MVT illuminated by a red laser diode could cause an involuntary accommodation in subjects. It was hypothesised that the monochromatic nature of the illumination (and not the holographic recording) was responsible for the involuntary accommodation when looking at an MVT illuminated by a red laser diode.

7.2

Method

Subjective refraction was performed to work out the spectacle correction required for subsequent holographic measurements. Subject recruitment and subjective refraction followed the same procedure and protocols as described in Chapters 2 and 3.

7.2.1 The modified simple optometer

A simple optometer was constructed using a +20 D lens. The optometer contained an MVT, which is a 3x3 array of match sticks located at different distances from the lens. Printed standard high contrast letters are pasted onto the forward-facing end of the sticks that are viewed by the subject.

The target and the light source are inside a light-tight black box with an aperture through which the subject views the target. At the aperture, a provision is made to place the SE spectacle correction of the subject, and an eye cup is provided close to the spectacle correction for the subject to place their eye.

7.2.2 Multi-vergence optometer

When the distance-corrected subject focuses into a multi-vergence image, they will see a range of high contrast letters with constant angular size (50’), each located at a difference vergence distance from the eye. For a distance-corrected subject, the clearest image vergence (at infinity) is conjugate with the retina (assuming that the subject is not accommodating). Rays from the image wavefronts closer than the far point of the eye will be diverging and will form optical images posterior to the retina. Likewise, converging rays from image wavefronts will form optical images anterior to the retina. Due to the depth of field and large character size, there will be a range of characters at difference vergences that would still remain clear. For vergences beyond this range, characters start to become blurry and eventually unrecognisable. The limit where positive blur becomes too ‘blurry’ for letter recognition to become possible (just recognisable limit) is the PBL.

With one eye patched, the other eye was given the spherical equivalent spectacle correction and subjects were asked to call out the letters that they could recognise. Since all subjects were distance-corrected, all subjects should have and did recognise the zero-vergence target as clear. Subjects were then encouraged to read as high up the multi-vergence target as possible, corresponding to hyperopic targets, with more converging wavefronts as they ‘read-up’ the multi-vergence target. This measurement gives an estimate of the PBL and is recorded down. Guessing was permitted and subjects were encouraged to do so without squinting.

Room lighting was under mesopic conditions, but had little effect on the contrast of target letters since the optometer was enclosed within a black box with its own illumination source (‘red’ laser diode). The cup-shaped eyepiece ensured external lighting did not enter the subject’s eye during measurements. The clinician that carried out subjective refraction subsequently performed the optometer experiment. However, the clinician was unaware of the character vergences and of the letter arrangement.

7.2.2.1 *Testing with Optometer A*

The letters presented to the subject through the multi-vergence target in the optometer had vergences intended to range from 0.00 to +4.00 D in 0.5 D steps. The optometer (Optometer A) therefore, consisted of no near-targets (myopic targets) or targets with diverging wavefronts. That is, with the exception of the zero vergence target, all other image wavefronts reaching the eye consist of only converging rays. Table 7.1 shows the target letter used as well, the desired vergence and the actual vergence measured in the optometer (A). Figure 7.1 shows the actual orientation and placement of the target image.

Table 7.1. Letter targets with the measured vergence for Optometer A.

Letter target	Expected vergence	Actual vergence (D)
R	0.00	0.00
A	+0.50	+0.47
N	+1.00	+0.96
K	+1.50	+1.47
P	+2.00	+1.95
B	+2.50	+2.56
H	+3.00	+3.02
F	+3.50	+3.59
S	+4.00	+4.20

Figure 7.1. Letter arrangement when viewed through the optometer.

7.2.2.2 *Testing with Optometer B*

Vergences of the optometer were then modified for a subsequent experiment where vergences were designed to range from -1.00 D to +3.00 D in 0.50 D steps. This optometer (Optometer B) had two myopic targets that were hypothesised to cause the involuntary relative lead of accommodation in some myopic subjects. Table 7.2 shows the target letter used as well, the desired vergence and the actual vergence measured in the optometer (B). The letter arrangement is the same as in optometer A (Figure 7.1).

Table 7.2. Letter targets with the measured vergences for Optometer B.

Letter target	Expected vergence (D)	Actual vergence (D)
R	-1.00	-1.06
A	-0.50	-0.54
N	0.00	0.00
K	+0.50	+0.56
P	+1.00	+1.08
B	+1.50	+1.76
H	+2.00	+2.26
F	+2.50	+2.88
S	+3.00	+3.54

Actual letters called out by the subject were recorded. The number of correct letters that the subject is able to recognise gives a measure of the amount of PBL of the subject. Pupil sizes were also recorded during preliminary examination under similar mesopic illumination using the pupil chart for Experiment 1 and Grand Seiko WAM 5500 autorefractor (Japan; http://www.grandseiko.com/english/WAM-5500e.htm) for Experiment 2.

7.2.3 Statistical consideration

Two-way analysis of variance (ANOVA) was used to test for the MLE by measuring the differences in PBL between optometer types (Optometer A, Optometer B) and refractive groups (myopia, hyperopia). A one-way analysis of covariance (ANCOVA) was also used to determine the effect of pupil sizes (small, large) on PBL responses in Optometer A and subsequently, Optometer B. Subjects were then grouped into different age groups (teenagers, young adults, presbyopes) and a one-way ANOVA was used to determine whether PBL responses varied with respect to age. Significance was set at 0.05 for all statistical tests, and a Bonferroni adjustment was made using IBM SPSS Statistics Version 20 for multiple comparisons where appropriate (unless otherwise stated).

Results

7.3

Sixty-seven subjects were recruited for this study, of which 25 subjects participated in Experiment 1 (optometer without myopic targets, Optometer A) and 42 participated in Experiment 2 (Optometer with myopic targets, Optometer B). The general descriptive statistics are shown in Tables 7.3 and 7.4 for optometers A and B respectively.

Table 7.3. Descriptive statistics for Experiment 1 (using Optometer A).

n = 25	Minimum	Maximum	Mean	Std. deviation
Age (years)	9	53	28	16
Mean sphere (D)	-6.25	+3.00	-0.90	2.04
PBL (D)	0	+2.81	+1.71	0.81
Pupil (mm)	4	6	5.0	0.6

Table 7.4. Descriptive statistics for Experiment 2 (using Optometer B).

n = 42	Minimum	Maximum	Mean	Std. deviation
Age (years)	6	63	32	18
Mean sphere (D)	-3.63	+1.75	-0.53	1.32
PBL (D)	-0.04	+2.56	+1.29	0.73
Pupil (mm)	4.1	8.0	6.4	1.1

Table 7.5. Descriptive statistics: PBL for myopic subjects

Optometer type	PBL mean (D)	Std. deviation (D)	N
A	1.51	0.85	16
B	1.19	0.65	26
Total	1.23	0.73	42

Table 7.6. Descriptive statistics: PBL for hyperopic subjects

Optometer type	PBL mean (D)	Std. deviation (D)	N
A	2.07	0.63	9
B	1.46	0.85	16
Total	1.75	0.75	25

The research aim was to determine whether the presence of the two myopic targets would reduce the PBL measured with Optometer B compared to that measured with Optometer A, and whether there was a difference between the PBL for myopic and hyperopic subjects.

Myopia was defined from the mean sphere as being equal to or less than -0.50 D measured from subjective refraction. Hyperopia was defined as having mean sphere +0.50 D or greater.

The PBL responses were subjected to a two-way ANOVA to compare the effects of refractive groups (myopia and hyperopia) and the two types of optometers (A and B).

The data satisfied the requirements for the statistics tests. Pupil size was excluded as a potential covariate because it lacked independence across refractive groups ($t_{(48)}$ = 2.178, P = 0.034).

Table 7.5 and 7.6 shows the descriptive statistics which compares the PBL for myopic and hyperopic subjects (respectively) between optometer A and B.

The main effect of optometer type yielded an F ratio of $F_{(1,63)}$ = 5.621, P = 0.021 indicating that the mean PBL for Optometer A (M = 1.71 D, SD = 0.81) was both statistically and clinically greater than the mean PBL for Optometer B (M = 1.29 D, SD = 0.74). This could be seen visually in Figure 7.2.

The main effect of refractive group conceded an F ratio of $F_{(1, 63)}$ = 4.513, P = 0.038) indicating that the mean PBL for hyperopic subjects (M = 1.68 D, SD = 0.82) was also clinically greater than the mean PBL for myopic subjects (M =1.31 D, SD = 0.74). This could be visually seen in Figure 7.3.

The interaction effect between optometer type and refractive error group was not-significant ($F_{(1, 63)}$ = 0.556, *ns*). This could be visually seen in Figure 7.4.

Additional ANCOVA analyses suggested that the variance in PBLs may be shared with the variance in pupil sizes (i.e. there was a small confounding effect), indicating that pupil size may also influence the PBL of subjects.

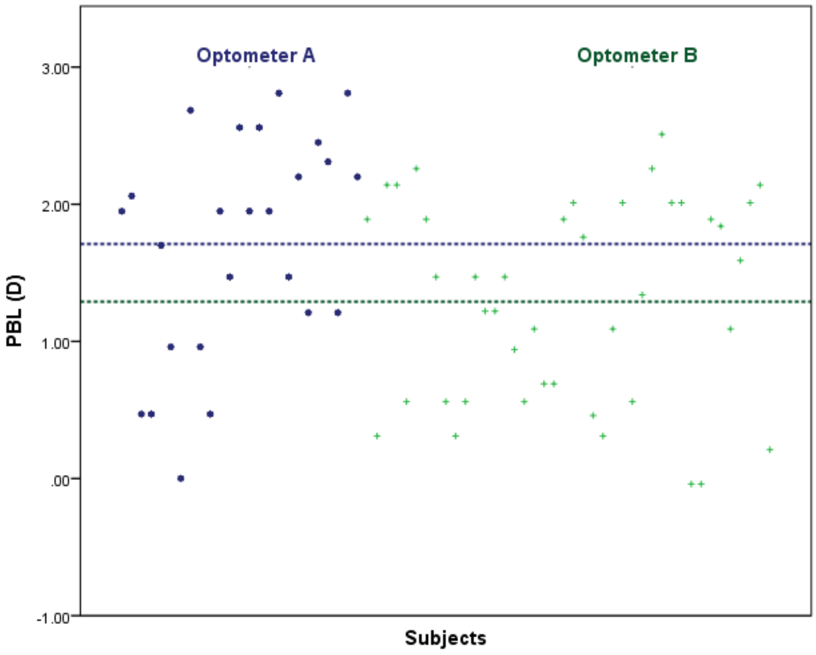

Figure 7.2. Scatter plot showing a lower average PBL in Optometer B.

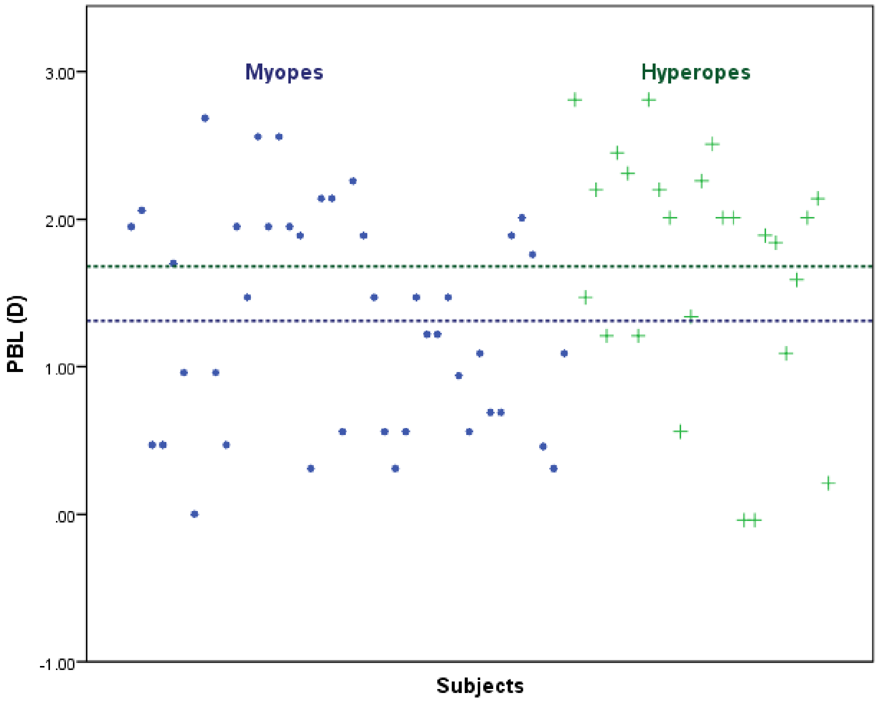

Figure 7.3. Scatter plot showing a lower average PBL in myopic subjects.

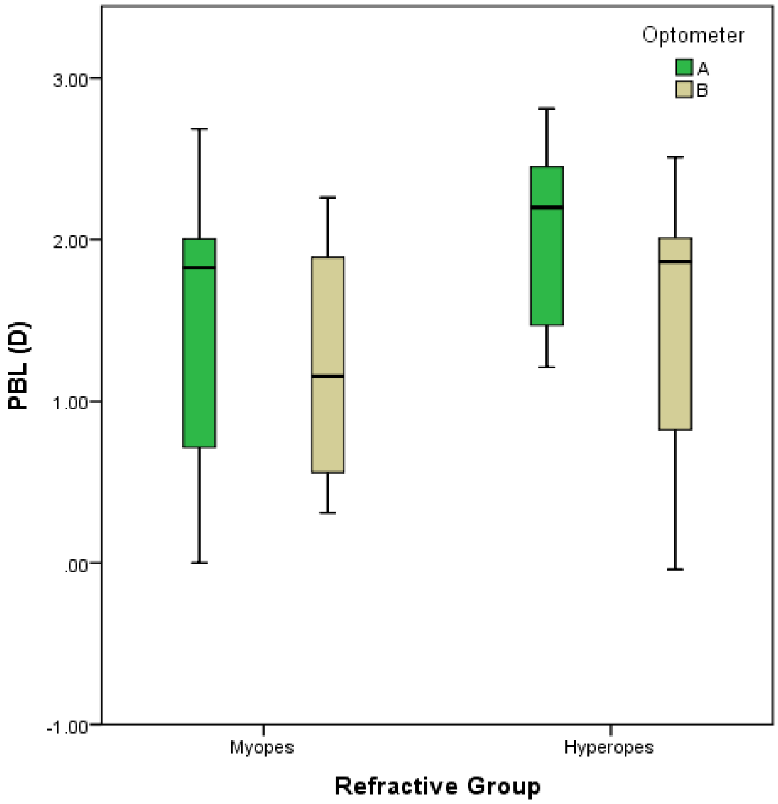

Figure 7.4. Box plot of myopic subjects vs. hyperopic subjects along with optometer type.

Using the average pupil size of 5.0 mm in Optometer A and 6.4 mm in Optometer B, subjects were divided into smaller and larger pupil size groups for each optometer type. The aim was to determine if the PBL would vary between different pupil size groups, with the expectation that a smaller pupil size reduced the blur circle on the retina, resulting in greater PBL across all refractive groups. Tables 7.8 and 7.9 show the descriptive statistics of this analysis for Optometer A whilst Tables 7.10 and 7.11 show the descriptive statistics for Optometer B.

Table 7.7. Descriptive statistics for smaller pupil groups in Optometer A.

n = 9	Minimum	Maximum	Mean	Std. deviation
Pupil (mm)	4.0	5.0	4.6	0.5
SE (D)	-6.25	+1.75	-1.07	2.18
Age (years)	9	53	28.18	17
PBL (D)	+0.47	+2.81	+1.82	0.72

Table 7.8. Descriptive statistics for larger pupil groups in Optometer A.

n = 9	Minimum	Maximum	Mean	Std. deviation
Pupil (mm)	5.00	6.0	5.3	0.5
SE (D)	-2.75	+1.50	-1.01	1.63
Age (years)	9	53	28	18
PBL (D)	+0.47	+2.69	+1.69	.84

In Optometer A, the mean pupil size in the smaller group was similar (p = 0.50) between myopic subjects (M = 4.8 mm, SE = 0.1 mm) and hyperopic subjects (M = 4.7mm, SE = 0.2 mm).

For the larger pupil group in Optometer A, mean pupil size was similar (p = 0.99) between myopic subjects (M = 6.0 mm, SE = 0.3 mm) and hyperopic subjects (M = 6.0 mm, SE = 0.4 mm).

7.3.1 Effect of pupil size on the PBL of myopic and hyperopic subjects (Optometer A)

A one-way ANCOVA was conducted to determine whether there was a statistically significant difference in PBL between pupil groups, with age as a covariate. PBL did not vary between the small pupil group (adjusted mean = 1.81 D, SD = 0.72 D) and large pupil group (adjusted mean = 1.58 D, SD = 0.82 D) ($F_{(1,16)}$ = 0.43, *ns*).

PBL responses with Optometer A were initially subjected to a two-way ANOVA between pupil size group (smaller, larger) and subjects' refractive type (myopia, hyperopia). The main effect of refractive type yielded an F ratio of $F_{(1,16)}$ = 0.478, *ns*, indicating that the mean PBL for myopic subjects (M = 1.65 D, SD = 0.81) was not statistically different to that for hyperopic subjects (M = 1.95 D, SD = 0.65).

The main effect of pupil size group returned an F ratio of $F_{(1, 16)}$ = 0.619, *ns*, indicating that the mean PBL for the smaller pupil group (M = 1.82 D, SD = 0.72) was also not statistically different to that for the larger pupil group (M =1.69 D, SD = 0.83). The interaction effect was again non-significant ($F_{(1, 16)}$ = 0.619, *ns*).

Age was subsequently applied as a covariate in a two-way ANCOVA to determine whether there were statistically significant differences in PBL between pupil size groups (smaller and larger) and refractive types (myopia, hyperopia) for Optometer A. The main effect of refractive group yielded an F ratio of $F_{(1,14)}$ = 0.282, *ns*, indicating that although the mean PBL for myopic subjects (M = 1.58 D, SD = 0.80) was lower than that for hyperopic subjects (M = 1.95 D, SD = 0.65), the result was probably due to chance. The main effect of pupil group returned an F ratio of $F_{(1, 14)}$ = 0.504, *ns,* indicating that the mean PBL for smaller pupil sizes (M = 1.82 D, SD = 0.72) was not significantly different to that for larger pupil sizes (M =1.58 D, SD = 0.82).

The interaction effect between pupil size group and refractive type was also not significant ($F_{(1, 14)}$ = 0.218, *ns*). Looking at simple effects, for the smaller pupil size group, hyperopic subjects had a greater PBL than myopic subjects (MD = 0.36 D, $F_{(1,14)}$ = 0.417, P = 0.53). This could be visually inspected from the box plot of Figure 7.5.

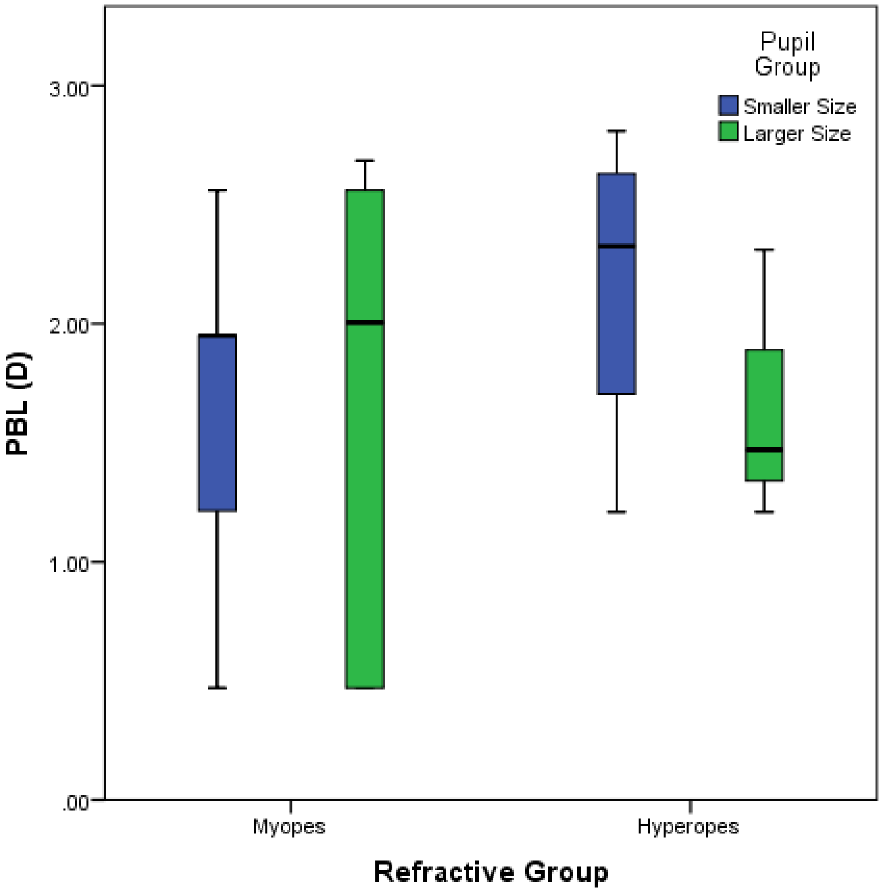

Figure 7.5. Average PBL (D) against refractive and pupil groups in Optometer A.

7.3.2 Effect of pupil size on the PBL of myopic and hyperopic subjects (Optometer B)

Table 7.9. Descriptive statistics for smaller pupil groups in Optometer B.

n = 10	Minimum	Maximum	Mean	Std. deviation
Pupil (mm)	4.1	6.2	4.8	0.6
SE (D)	-1.75	+1.75	+0.39	1.17
Age (years)	23	63	49	14
PBL (D)	+0.21	+2.51	+1.48	0.75

Table 7.10. Descriptive statistics for larger pupil groups in Optometer B.

n = 32	Minimum	Maximum	Mean	Std. deviation
Pupil (mm)	5.5	8.0	6.9	0.6
SE (D)	-3.63	+1.25	-0.82	1.24
Age (years)	6	57	26	16
PBL (D)	-0.04	+2.26	+1.24	0.73

In Optometer B, the mean pupil size in the smaller group was similar (P = 0.79) between myopic subjects (M = 4.7mm, SE = 0.3 mm) and hyperopic subjects (M = 4.6 mm, SE = 0.2 mm). Mean pupil size for the larger pupil group was also clinically similar (P = 0.07) between myopic subjects (M = 7.0, SE = 0.1 mm) and hyperopic subjects (M = 6.6 mm, SE = 0.2 mm).

A one-way ANOVA was conducted to determine whether there was a statistically significant difference in PBL between pupil groups in Optometer B. Age was excluded as a covariate because it was not independent across pupil groups ($t_{(20)}$ = 8.94, P <.005). PBL did not vary between small pupil (adjusted M = 1.48 D, SD = 0.75 D) and large pupil (M = 1.24 D, SD = 0.73 D) groups ($F_{(1,40)}$ = 0.817, P = 0.37). This shows that PBL responses appear to be independent of large or small pupil sizes. The descriptive statistics for this analysis is shown in Tables 7.9 and 7.10.

The PBL for Optometer B was also examined according to refractive group (myopia and hyperopia) and pupil size group (smaller, larger) using two-way ANOVA. The aim was to determine if pupil size differences could help to explain the difference in PBL between myopic and hyperopic subjects.

The main effect of refractive group yielded an F ratio of $F_{(1,38)}$ = 1.712, *P* = 0.20, indicating that the mean PBL for myopic subjects (M = 1.19 D, SD = 0.65) was not statistically and clinically different to that for hyperopic subjects (M = 1.46 D, SD = 0.85), regardless of the pupil group. The main effect of pupil size group returned an F ratio of $F_{(1, 38)}$ = 0.088, *ns*, indicating that the mean PBL for smaller pupil sizes (M = 1.48 D, SD = 0.75) did not significantly different to that for larger pupil sizes (M = 1.24 D, SD = 0.73).

The interaction effect was also not significant, $F_{(1, 38)}$ = 1.146, *P* = 0.29). Analysis of the simple effects indicated that hyperopic subjects again, had a larger PBL than myopic subjects (MD = 0.70 D, $F_{(1,38)}$ = 1.874, *P* = 0.179) in the smaller pupil group (Figure 7.6).

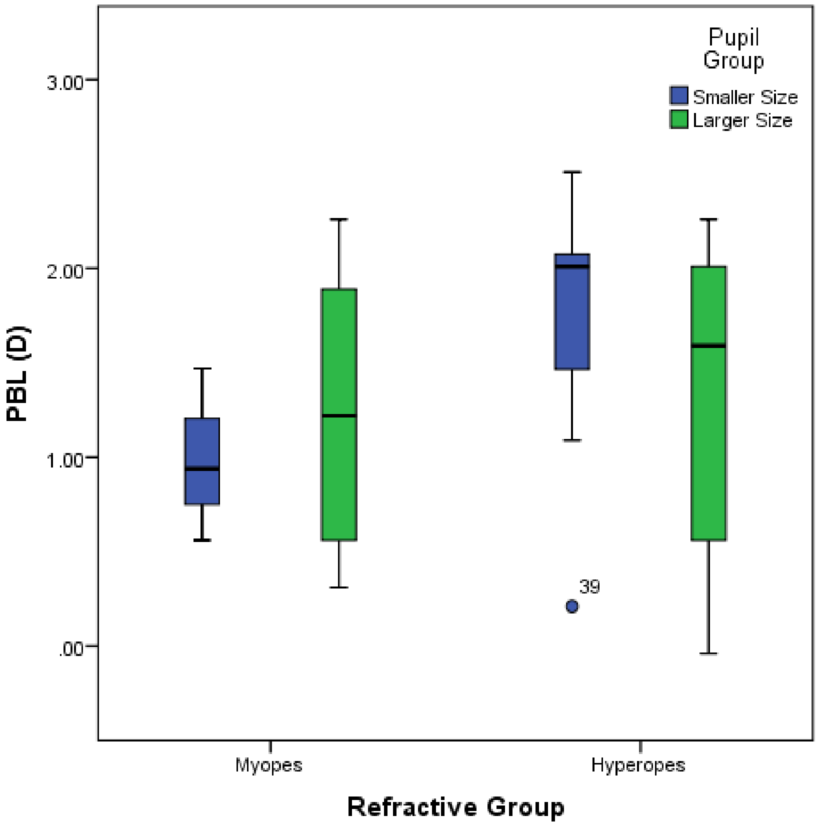

Figure 7.6. Average PBL (D) against refractive and pupil groups in Optometer B.

7.3.3 Effect of age on the PBL in Optometer A and Optometer B (independent of refractive error)

Subjects were grouped according to their ages as either under 20-years-old (teenagers), 20 to 40-years-old (young adults), or over 40-years-old (presbyopes), to determine if age had any influence on PBL. A one-way ANOVA was conducted to determine whether there was a statistically significant difference in PBL response between the different age groups (teenagers, young adults, presbyopes). Separate analyses were done for Optometer A and Optometer B. Table 7.11 shows the descriptive statistics according to age for optometers A and B.

For Optometer A, there was no significant difference in PBL between age groups ($F_{(2, 20)} = 1.702$, $P = 0.21$) and this can be observed visually in Figure 7.7. On the contrary, for Optometer B, there was a significant difference in PBL between age groups as determined ($F_{(2,37)} = 10.163$, $p < .0005$). A Tukey post-hoc test showed that PBL responses for young-adults (MD = 0.78D, *SE* 0.16 D) were significantly lower than those for both the teenager (MD = 1.46 D, SE 0.15 D, $P = 0.012$) and presbyopic (MD = 1.77 D, SE = 0.15 D, $P < 0.0005$) groups. There were no statistically significant differences between the teenager and presbyopic ($P = 0.325$) groups. The plot of Figure 7.8 shows this difference visually.

Table 7.11. Descriptive statistics according to age in optometers A and B.

	Age group	Mean	*SE*	SD
	Teenagers	1.51	0.23	0.84
Optometer A	Young-adults	1.29	0.34	0.94
	Presbyopes	2.05	0.29	0.41
	Teenagers	1.46	0.15	0.72
Optometer B	Young-adults	.78	0.16	0.46
	Presbyopes	1.77	0.15	0.47

The homogeneity of variance assumption was considered to be satisfied with Levene's Test of Equality of Error Variance (*P* = 0.15) for Optometer B. The standard deviations (Table 7.11) across groups were not too different, suggesting that ANOVA was robust enough to be used in this situation (Howell, 2007).

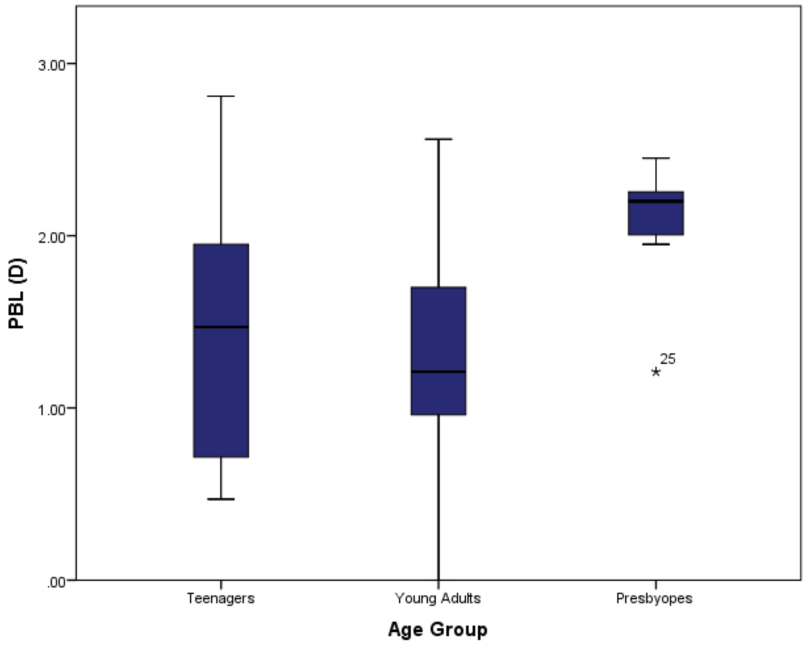

Figure 7.7. Box plot showing PBL against age groups in Optometer A.

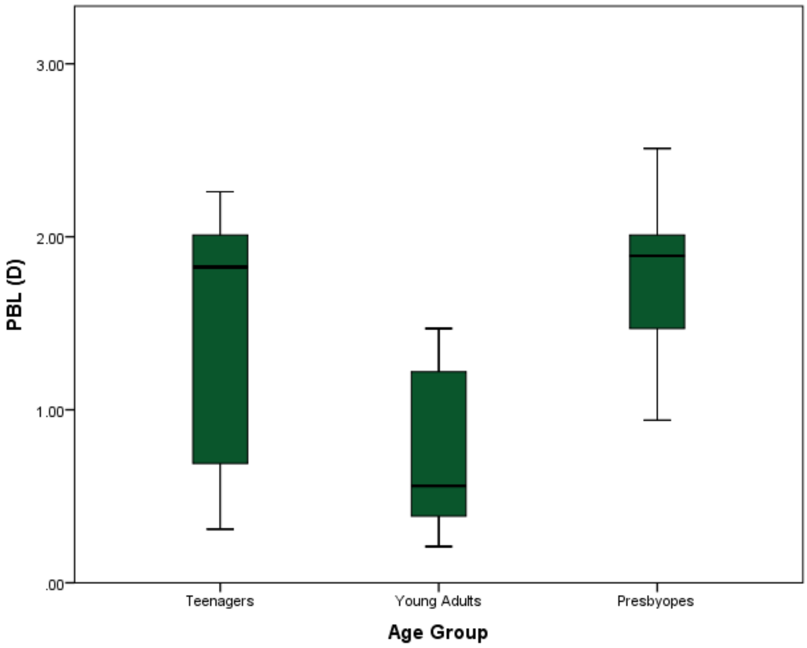

Figure 7.8. Box plot showing PBL against age groups in Optometer B.

7.4 Discussion

7.4.1 Difference between myopia and hyperopia

A difference in the PBL between myopic and hyperopic subjects was observed independently of optometer type under ‘red’ monochromatic illumination. The difference in PBL indicates an MLE being observed in myopic subjects (lower PBL), and suggests that the multi-vergence nature of the target causes an involuntary accommodation in some myopic subjects. This effect was absent when PBL was measured with a single-vergence holographic logMAR chart or a logMAR chart under coherent ‘red’ illumination (Chapter 6), and again suggest the importance of the MVT for the MLE. This study showed that the hologram was not a requirement for the MLE, since the effect was reproducible in an optometer using coherent ‘red’ illumination.

Figure 7.9 attempts to simulate the view of a lower PBL (myopic group) and Figure 7.10 simulates the view of a higher PBL (hyperopic group).

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Figure 7.9. Simulated view of a low PBL.

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Figure 7.10. Simulated view of a high PBL.

A hologram was unique because it reconstructed the original scene for viewing at a later time, in contrast to the optometer where observations and measurements were taken in real time. the author thought that the pseudo-stereoscopic nature of the reverse-conjugated wavefront in the hologram had an unnatural effect, which could have resulted in a greater involuntary accommodation in myopic subjects than in hyperopic subjects. This study showed that this was not the case, since MVE was observable in myopic subjects using an optometer, and was independent of holography.

Myopic subjects are more prone to the effect of the MVT than hyperopic subjects with myopic subjects focusing about 0.50 D more inwards than hyperopic subjects, a possible lead of accommodation. It is known that late-onset of some myopic people's dark focus shifts closer under cognitive or accommodative tasks, with effects persisting for a while after the task (Bullimore & Gilmartin, 1987; McBrien & Millodot, 1988). People with late-onset myopia could also have a reduced ciliary muscle sympathetic innervation (Cogan, 1937; Vasudevan, Ciuffreda, & Gilmartin, 2009), resulting in stronger accommodative amplitude. The closer the near-target, the greater the deficit (McBrien & Millodot, 1988), and the greater accommodative amplitude may explain a greater involuntary accommodation in some myopic individuals. Although the proportion of individuals with late onset myopia in this study was unknown, it may have partly contributed to the differences observed between the refractive groups (myopia and hyperopia). There is a tendency for the eye to leave the 'red' focus on the retina when fixating on remote objects, and this results in a lead of accommodation (Keirl & Christie, 2007). Could it be that myopic subjects have a greater or stronger tendency to accommodate with the red light? If so, this could explain the difference observed between myopic and hyperopic subjects. It might also explain the tendency for some young myopic individuals to continually have a red preference when viewing the duochrome chart, even when over-corrected with negative lenses.

Table 7.12. Descriptive statistics: PBL multi-vergence target with near-targets in a hologram[†].

Refractive group	Mean	Std. deviation	Minimum	Maximum	N
Myopia	+1.07	0.70	0.00	+2.45	29
Hyperopia	+1.94	0.50	+0.46	+2.45	30
Combined	+1.51	0.74	0.00	+2.45	59

[†] Results from previous studies (Nguyen et al., 2012, 2013)

Table 7.13. Descriptive statistics: PBL multi-vergence target in Optometer B.

Refractive group	Mean	Std. deviation	Minimum	Maximum	N
Myopia	+1.19	0.65	+0.31	+2.26	26
Hyperopia	+1.46	0.85	-0.04	+2.51	16
Combined	+1.29	0.74	-0.04	+2.51	42

Optometer B and holographic MVT from previous studies (Table 7.12, data reproduced here for reader convenience) were similar because both had two near-targets located at approximately 0.50 m and 1.0 m. Based on a previous study of the multi-vergence target (with two near-targets) in a hologram (see Table 7.12), the results compared well with Optometer B (Table 7.13), with a difference of 0.12 D for myopic subjects ($t_{(53)} = 0.637$, $P = 0.53$), but not so much for hyperopic subjects (MD = 0.48 D, $t_{(44)} = 2.408$, $P = 0.028$). A difference was observed in hyperopic subjects probably because, in a hologram, subjects are viewing through an open-field (free space) hologram plate, which is clear and uses no lenses. In contrast, for the optometer, subjects are looking into a small box instrument through a +20 D lens. The optometer may be inducing more instrumental myopia in hyperopic subjects than the hologram, suggesting partial involuntary accommodation by hyperopic subjects. Instrumental myopia in the optometer may not be affecting myopic subjects as much, because myopic subjects are already accommodating due to the MLE.

Certain subjects are prone to the MLE and accommodate involuntarily when presented with 50’ size targets near their visual axis at multiple vergence distances. On average, myopic subjects appear to be affected more than hyperopic subjects, and it is questionable as to whether there is an association between reduced PBL and the development of myopia. It would be of interest to monitor these subjects over time to find any association.

7.4.2 Optometer type: effect of myopic targets

PBL responses in Optometer B (with myopic targets) were on average lower than those in Optometer A (without near-targets), with a mean difference of 0.42 D (*P* = 0.021). The two extra near-targets in Optometer B had the effect of reducing the PBL by nearly 0.50 D and were independent of refractive error. This is similar to a study by Stark & Atchison, where an intervening screen placed at 50 cm or near the individual’s dark focus while looking at a distant letter chart, also showed an MLE (Stark & Atchison, 1998). This study showed that an MVT under red laser diode illumination also had a similar effect without the need for a full intervening screen. It appears that two small 50’ size target located at 2.0 m and 1.0 m near the visual axis was enough to elicit a stronger MLE. It is unclear if the effect was triggered by the 0.5 D or 1.0 D target, but the author suspect that the 1.0 D target, being closer to the dark focus, would stimulate a stronger MLE.

7.4.3 Dark focus and the Mandelbaum Effect

It is commonly known that when the visual stimulus is degraded, the eye will involuntarily relax to an intermediate distance called the ‘dark focus’ or ‘tonic accommodation’ (Artal et al., 2012; Epstein, 1982; Rosenfield, 2006).. Furthermore, when there are conflicting visual targets occupying the same visual space (such as a distance letter chart and intervening screen), the eye also involuntarily accommodates to an intermediate distance. This effect is known as the Mandelbaum Effect

(Mandelbaum, 1960; Owens, 1979). The accuracy of accommodation is dependent on the quality of the stimulus, and the accommodative response usually becomes inaccurate with weaker stimulation. With very weak stimulation, accommodation gets locked to dark focus position, regardless of target or stimulus distance (Johnson, 1976). In this study, coherent red illumination is already a weak stimulus for accommodation (as discussed initially in Chapter 3). This may have caused the involuntary accommodation in some subjects. Furthermore, the effect could have been compounded by the Mandelbaum Effect. Although there is no intervening screen, the appearance of multiple near targets in close proximity to each other could have triggered some involuntary accommodation as well.

A similar effect was already observed in myopic subjects in a multi-vergence target in a hologram, where the myopic subjects appear to have accommodated more than hyperopic subjects by about 0.85 D (Chapters 5 and 6).

The author initially thought of laser speckle (from monochromatic light) scattered homogenously over the target could have contributed to the MLE. However, recent research with a logMAR chart using coherent lighting failed to elicit the MLE (Chapter 6) and suggests that speckle from the coherent lighting alone is not enough to bring out the MLE. Instead, it was probably the multiple targets at different vergences that resulted in an involuntary accommodation in some subjects in this study.

7.4.4 Effect of pupil size

Smaller pupil size reduces the blur circle on the retina, results in a greater depth of focus, and increases the PBL. Larger pupil size increases aberration effects of the eye and should result in reduced PBL. Pupil size could be a confounding factor to the differences observed, and thus, it was worthwhile analysing the effect of pupil size in this study.

In Optometer A, the PBL responses for the smaller pupil group were slighter higher than those of the larger pupil group, and could not account for the entire MLE (MD = 0.23 D, *P* = 0.43). Myopic subjects in the smaller pupils group still had a smaller PBL compared to hyperopic subjects (MD = 0.36, *P* = 0.53). A power analysis was initially performed to determine the optimal sample size to test the primary goal of a difference in PBL between the different refractive groups. To study the effect of pupil size on PBL, subjects with similar pupil sizes were separately analysed to determine if the effect was still apparent. As a result, the sample size was reduced with the effect of weakening the power of the test. Statistical significance was not reached probably because of an insufficient sample size.

For Optometer B, the smaller pupil size group also had a greater PBL response compared to the larger size group (MD = 0.24 D, *P* = 0.372). This was consistent with Optometer A and was expected because of the greater depth of focus. The myopic group continued to have lower PBL than the hyperopic group (MD = 0.70 D, *P* = 0.18). Once again, although the difference was clinically significant, statistical significance was not reached probably because of the small sample size. The larger pupil size group for both Optometer A and B had no clinical differences between myopic and hyperopic subjects.

When the eye's pupil size is reduced, there is also a shift in accommodation towards the dark focus (Hennessy, Iida, Shina, & Leibowitz, 1976) which may explain the reduced PBL in myopic subjects. However, this is probably caused by the loss of the accommodation control system rather than degradation of the visual stimulus, as is the case for the Mandelbaum Effect. When the eye accommodates or focuses without a noticeable increase in the quality of the image, the eye would relax to the dark focus position. In this particular case, a small pupil increases the eye's depth of focus, resulting in the loss of accommodative responsiveness and shift towards the dark focus. However, if this was to happen, then the PBL response would be lower and would explain for the lower PBL in myopic subjects. The smallest pupil sizes were 4.0 mm and 4.1 mm for Optometer A and Optometer B, respectively, and pupil sizes were not small enough to shift the refractive state of the eye to the dark focus and reduce PBL.

Younger subjects have greater amplitude of accommodation (A_{amp}), and one cannot help but wonder if this had any bearing on the results. Could the mild involuntary accommodation observed in some subjects be related to their accommodative amplitude (A_{amp})? A greater A_{amp} in reserve could enable a greater propensity for the subject to exert some effect, and focus closer than infinity. This is in hindsight, and the author did not measure A_{amp} for each subject. However, there are well-accepted correlations between age and accommodative amplitude, such as Donder's table of age-expected A_{amp} (Table 7.14).

Table 7.14. Donder's table of age-expected amplitude of accommodation.

Age	Amplitude	Age	Amplitude
10	14.00	45	3.50
15	12.00	50	2.50
20	10.00	55	1.75
25	8.50	60	1.00
30	7.00	65	0.50
35	5.50	70	0.25
40	4.50	75	0.00

Contrary to expectation, greater A_{amp} did not result in greater involuntary accommodation and reduced PBL. Younger adults (between 20 and 40 years old) had a lower average PBL than teenagers (<20 years old) by about 0.23 D (P = 0.85) for Optometer A and 0.68 D (P = 0.012) for Optometer B.

In this study, it appears that young adults were more susceptible to the MLE than teenagers or presbyopes. This is understandable for presbyopes, but difficult to fathom in teenagers since they have better accommodation (because of their age).

It appears that the mechanism that causes the MLE is not related to the amplitude of accommodation, with the effect being slightly more prominent in young adults than in younger teenagers. This is interesting since one of my earlier studies found that in pre-presbyopes, a higher PBL was more inclined to have greater myopic progression (Avudainayagam, Avudainayagam, & Nguyen, 2015). This finding appears to be in agreement with this study, since the younger teenage group with their higher relative PBL would also have had a greater myopic progression (Hyman et al., 2005) than the young-adult group.

7.4.5 Real-world influences of the MLE

Adding two 50′ size targets at 0.5 m and 1 m in front of the subject's visual axis resulted in an average involuntary accommodation of nearly 0.50 D ($p = 0.021$). Although the statistics may not be very strong, the chance of making a type 1 error is still quite remote (2.1%). This involuntary accommodation is similar to the Mandelbaum Effect with the exception that visual stimuli do not need to be superimposed or conflicting. Although the effect is small, it still has clinical and practical significances. As an example, a 50′ stimulus at 50cm is about 7mm in size and about 14mm at 1m. This can often be the size of dirt splatters, bird's droppings, water splashes or stone chips on the windscreen of automobiles. If these are located near the visual axis of the driver, then the refractive error of most drivers could potentially be reduced by 0.50 D. Since variability is high, refractive error could potentially be reduced by 1.50 D in some individuals. This involuntary accommodation has the capacity to debilitate a driver that already has borderline vision for adequate driving. Another example is the more frequent use of head-up displays (also known as HUDs, see Figure 7.11) where a transparent display is used to display information in front of the operator (near their visual axis). HUDs are often used in aircraft and automobiles and were intended to permit the pilot or driver to view both the external environment and the display (HUD) without having to look down at the lower instrument panel.

This image was
intentionally removed

Figure 7.11. HUD in an aircraft. Information located near
the pilot's visual axis may compromise vision in some individuals.

Although HUDs are convenient, the information on the HUD could possibly cause an involuntary accommodation in some operators because of the multiple stimuli near the operator’s visual axis. Efficient operation of the vehicle/craft is reduced and can result in poorer performance. Since safety is in question, further research into IA is essential to understand more about the ‘Mandelbaum-like Effect’ and the deterioration of vision when operating these vehicles.

The average involuntary accommodation in myopic subjects was higher than hyperopic subjects, although the effect was clinically low (about 0.40 D, $p = 0.038$). However, there was high variability in the study and PBL could be as high as 1.50 D in some subjects. As was discussed previously, this can be detrimental to drivers or pilots as the MLE can temporarily render these people slightly myopic. In a clinical setting, if the optical correction is already optimum, but the patient is still complaining of vision problems in dim light, then the clinician should also consider the effects of involuntary accommodation. In the case of poor vision when driving, this could be from night myopia (dark driving environments), empty field myopia (driving while looking at featureless environments such as the sky), the Mandelbaum effect (driving with Mesh protected windscreens), and the MLE (such as driving with dirty patches on windscreen, see Figure 7.12).

Figure 7.12. Left photo: An observer sees the clear house and sky unaffected by the dirty windscreen.
Right photo: An involuntary accommodation (~1D) towards the dirty windscreen results in blurring of the building and sky.

7.5 Conclusion

Under ‘red’ coherent lighting, multiple high-contrast 50’ size characters located at different vergences near the visual axis appears to cause an involuntary accommodation in some subjects, resulting in myopic subjects having a reduced PBL compared to hyperopic subjects. The introduction of two near-targets to the optometer resulted in a greater reduction in PBL across all refractive groups. The two near-targets caused a greater involuntary accommodation in both myopic and hyperopic subjects. After attempting to control for pupil differences, myopic subjects continued to show a reduced PBL (in the smaller pupil group) in both Optometers A and B. This suggests that the PBL difference observed between myopic and hyperopic subjects was not due to differences in pupil size.

Predicting myopic progression using holography

Chapter 8

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Introduction

8.1

The multi-vergence hologram is a phase hologram that resembles a transparent glass plate in appearance and contains a holographic record of real and virtual images of various test characters located at different distances from the eye (Nguyen et al., 2012). When this hologram is suitably illuminated with light from a low power He-Ne laser, a subject viewing through the hologram would see test characters of fixed angular sizes at various distances. In the hologram that the author used for the current study, the real images seen through the hologram were located from 1 m in front of the eye to infinity in front of the eye. The range of the virtual images seen through the hologram extends from about 15 cm behind the eye to infinity behind the eye. A spectacle-corrected subject viewing through this hologram should see the real images of the test characters clearly by exercising their accommodation. The test characters corresponding to the virtual images recorded in the hologram should appear blurred to the subject as a subject cannot exercise negative accommodation. The maximum amount of positive blur in a test character whereby the character is just recognisable by the subject is defined in this study as the PBL of the subject. The author measured the PBL for various spectacle-corrected subjects in an earlier study and found that the PBL for hyperopic subjects was about 0.9 D greater than that for myopic subjects (Chapters 5 and 6). This difference was statistically significant. The mean PBL for myopic subjects was close to +1 D and for hyperopic subjects, it was close to +2.00 D. The mean PBL for emmetropic subjects, on the other hand, was around +1.4 D, a value that lies in between the mean for hyperopic subjects and the mean for myopic subjects. The author also observed in an earlier study that some emmetropic subjects responded like myopic subjects and some emmetropic subjects responded like hyperopic subjects. This led me to wonder if the test with the hologram could serve as an indication of the development of myopia/ hyperopia. Furthermore, while the mean PBL for myopic subjects was around +1 D, some myopic subjects had a significantly higher limit blur (+2 D). Was there any association between myopic progression and the different levels of blur limits? So the author looked at the spectacle correction and the progression rate of myopia in the later years, where it was available, for the myopic subjects who participated in my previous studies with the hologram. The author found that the mean PBL of progressive myopic subjects was significantly greater than the mean PBL of non-progressive myopic subjects by about 0.8 D. None of the non-progressive myopic subjects responded like hyperopic subjects. This finding suggested that the special hologram could be used to test for progressive myopia. In this paper, the author present the test for progressive myopia and the initial results obtained. Further, investigation of the results obtained with the multi-vergence hologram also suggested that progressive myopic subjects have some latent accommodation like hyperopic subjects. In this paper, the author discusses the role of latent accommodation in the measurement and correction of ametropia using a phoropter in the clinic and its possible consequence on the development of progressive myopia. The author also presented results which show that the hologram was capable of confirming whether low ametropia measured using a phoropter in the clinic was indicative of either myopia or hyperopia. It was discovered that the hologram was able to classify all subjects into two distinct categories: one with latent accommodation and the other without any latent accommodation.

The aim of this study was to investigate whether there is any association between involuntary accommodation to a holographic MVT and myopic progression. It was hypothesised that subjects with an involuntary accommodation in the hologram were more prone to become myopic or to have myopic progression. The details of this investigation and subsequent findings are presented in this chapter.

8.2 Methods

8.2.1 The multi-vergence hologram

Refer to Chapter 2 for a description of the MVT hologram and the PBL measurement.

8.2.2 Subjects

The spectacle correction in the later years for 25 myopic subjects who participated in my earlier studies on the measurement of the PBL with the multi-vergence hologram was obtained from clinical records. Ethics approval was obtained from the UNSW Human Research Ethics Committee. The mean sphere of the spectacle correction (MS) for the myopic subjects was in the range of −0.375 D to −5.5 D. The astigmatism of the subjects included in the study was ≤ 0.5 D. The spectacle correction recorded for the subjects was determined by subjective refraction in the clinic using a phoropter. The maximum plus lens for best visual acuity was the criterion for the subjective end point. The best corrected visual acuity was 6/7.5 or greater and the subjects had no significant pathology. Using the data obtained from the records, the rate of progression of myopia was calculated for these subjects and the subjects whose progression rate was greater than or equal to −0.20 D per year were classified as progressive myopic subjects and the others as non-progressive myopic subjects.

Results

8.3

8.3.1 The test for progressive myopia

The initial mean sphere, age, time elapsed before the next refraction, mean sphere after the time elapsed, the PBL that was obtained with the hologram in their first visit and the progression rate of myopia have been shown in Table 8.1 for non-progressive myopic subjects and in Table 8.2 for progressive myopic subjects. The data obtained on the emmetropic subjects have been shown in Table 8.3. The pupil size when it was recorded was also included. The measurements were made in a dimly lit room and the pupil size was measured in the fellow eye using the digital pupillometer from NeurOptics (Model 59001).

The PBL was plotted against the mean sphere for the non-progressive myopic subjects in Figure 8.3 and for the progressive myopic subjects in Figure 8.4. The mean PBL for non-progressive myopic subjects was 0.55 D, with a standard deviation of 0.33 D. The mean PBL for progressive myopic subjects was 1.32 D, with a standard deviation of 0.75 D. Thus, the mean PBL for the progressive myopic subjects was 0.77 D greater than that for the non-progressive myopic subjects, and this difference was statistically significant in a one-tailed t-test, with a *P*-value of 0.0018 obtained for unequal variances.

The view obtained through the hologram has been simulated for non-progressive myopic subjects in Figure 8.3 and for progressive myopic subjects in Figure 8.4, respectively. The upper limit for the PBL of non-progressive myopic subjects at the 95% confidence level was 1.21 D. To test for progressive myopia using the criterion that any subject with a PBL greater than 1.21 D is a progressive myope, seven out of the 13 progressive myopic subjects pass this threshold and thus would be counted as true positives — giving 54% sensitivity for the test (Table 8.2). From Table 8.1, it can be seen that none of the non-progressive myopic subjects satisfied this criterion, and thus they would fail the test as true negatives giving 100% specificity for the test.

Table 8.1. Data on the mean sphere measured initially and with a time lapse for non-progressive myopic subjects who participated in the study with the hologram.

Subject Number	Initial age (years)	Initial mean sphere (D)	Time elapsed (years)	Mean sphere after time elapsed (D)	Progression rate (D per year)	PBL (D)	Pupil size (mm)
1	38	-0.375	1.92	-0.50	-0.07	0.07	6.1
2	33	-0.375	4.06	-0.75	-0.09	0.59	-
3	35	-0.50	1.74	-0.50	0.00	0.96	4.1
4	19	-0.50	4.34	-1.25	-0.17	0.46	-
5	8	-0.75	2.67	-1.125	-0.14	0.46	6
6	18	-1.375	2.58	-1.50	-0.05	1.01	-
7	11	-2.75	3.71	-3.25	-0.13	0.46	7.3
8	17	-3.125	1.10	-3.125	0.00	1.01	7
9	28	-3.375	1.00	-3.375	0.00	0.59	5
10	17	-4.375	2.95	-4.375	0.00	0.59	-
11	25	-5.25	2.08	-5.50	-0.12	-0.06	6.9
12	25	-5.50	2.08	-5.625	-0.06	0.46	6.7
Mean:	22.8	-2.35	2.57	-2.76	-0.07	0.55	6.1
Std dev:	9.5	1.96	1.12	1.86	0.06	0.33	1.1

Table 8.2. Data on the mean sphere measured initially and with a time lapse for progressive myopic subjects who participated in the study with the hologram.

Subject number	Initial age (Years)	Initial mean sphere (D)	Time elapsed (years)	Mean sphere after time elapsed (D)	Progression rate of myopia (D per year)	PBL (D)	Pupil size (mm)
1	8	-0.375	2.95	-3.25	-0.98	0.59	6.7
2	10	-0.75	3.2	-1.625	-0.27	0.46	6.5
3	14	-1	1.2	-1.75	-0.62	1.38	-
4	11	-1.125	3.75	-3.00	-0.5	0.59	8.3
5	9	-1.25	3.4	-4.00	-0.81	0.46	7.4
6	13	-1.375	4.07	-4.00	-0.64	1.26	6.7
7	18	-1.375	4.11	-2.5	-0.27	0.59	7.2
8	13	-1.5	3.73	-2.25	-0.2	1.95	7.2
9	15	-1.625	3.92	-5.00	-0.86	2.44	5
10	16	-2.375	0.97	-2.75	-0.39	2.08	7.4
11	11	-3	0.93	-3.5	-0.54	1.13	6.5
12	23	-3.75	3.85	-4.75	-0.26	1.95	5.8
13	15	-4	3.3	-5.5	-0.45	2.32	6.5
Mean:	13.5	-1.81	3.03	-3.38	-0.52	1.32	6.8
Std dev:	4.1	1.13	1.19	1.23	0.25	0.75	0.8

Table 8.3. Data on the mean sphere measured initially and with a time lapse for emmetropic subjects who participated in the study with the hologram.

Subject number	Age (years)	Initial mean sphere (D)	Time elapsed (years)	Mean sphere after time elapsed (D)	Progression rate (D per year)	PBL (D)	Pupil size (mm)
1	13	0	4.25	-0.125	-0.03	0.46	6.7
2	38	-0.25	2	-0.375	-0.07	0.88	5.8
3	17	-0.25	3.36	-0.50	-0.07	0.88	6.5
4	37	0.25	3.67	0.375	0.03	0.63	-
5	48	-0.125	3.17	0.125	0.08	1.01	-
6	23	-0.25	3.08	-0.25	0.00	0.88	4
7	24	0.25	4.97	-0.375	-0.13	0.46	-
8	28	0	1.4	0	0.00	0.88	-
9	30	0	3.08	0	0.00	1.95	4.5
10	11	0	4.17	-1.875	-0.45	1.95	5
11	50	0.25	1.08	0.50	0.23	2.07	-
Mean:	29	-0.01	3.11	-0.23	-0.04	1.1	5.4
Std.dev:	13.2	0.2	1.21	0.63	0.17	0.6	1.1

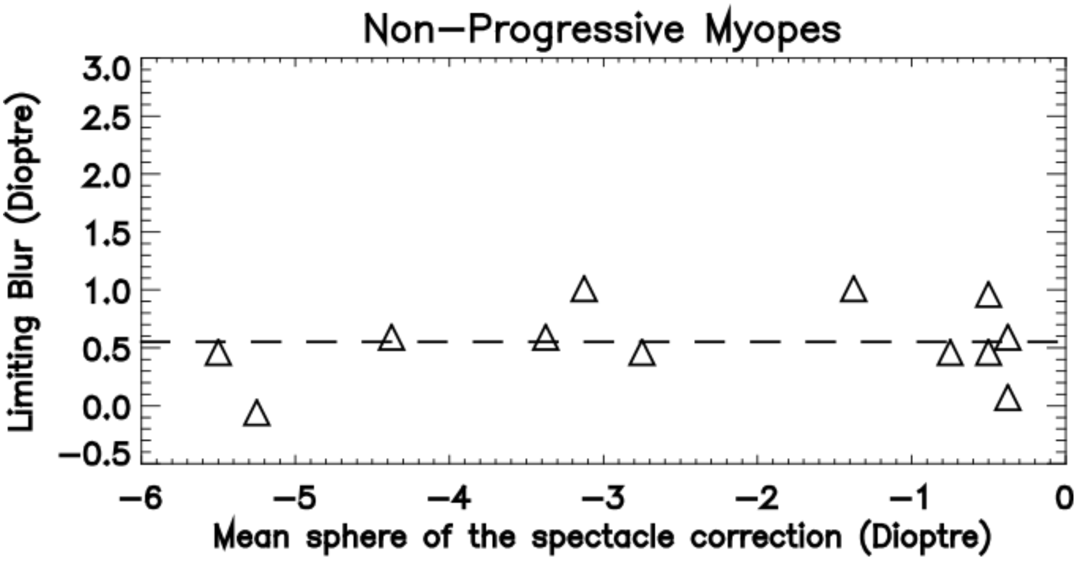

Figure 8.1. Plot of the PBL vs. the mean sphere of the spectacle correction for non-progressing myopic subjects. The dashed line indicates the mean PBL. Duplicated from Avudainayagam (2015).

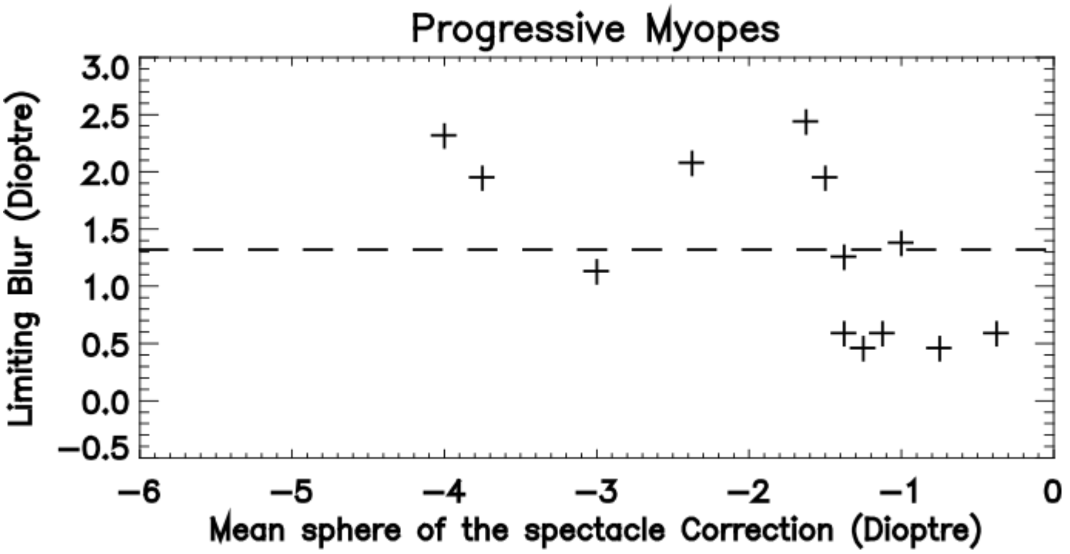

Figure 8.2. Plot of the PBL vs. the mean sphere of the spectacle correction for progressive myopic subjects. The dashed line indicates the mean PBL. Duplicated from Avudainayagam (2015).

Table 8.4. Data obtained with the hologram for myopic subjects.

Serial number	Age (years)	Mean sphere of the spectacle correction (Dioptre)	Number with most positive vergence recognised	PBL through the hologram (Dioptre)
1	25	-7.625	2	1.005
2	11	-3.25	4	1.95
3	19	-3.25	3	1.38
4	11	-2.875	1	0.585
5	31	-2.375	1	0.585
6	20	-2.25	2	0.88
7	11	-1.5	3	1.38
8	17	-1.375	1	0.585
9	18	-1.375	2	1.005
10	29	-1.25	2	0.88
11	35	-1.25	4	1.95
12	32	-1.125	3	1.505
13	14	-1	3	1.38
14	21	-1	2	0.88
15	46	-0.75	4	1.95
16	19	-0.5	1	0.46
17	42	-0.5	2	0.88
18	33	-0.375	1	0.585
19	35	-0.375	2	0.88

Mean: 1.09 D

Std dev: 0.488 D

Reproduced from (Nguyen et al., 2012), Table-2, P1177.

Table 8.5. Data obtained with the hologram for hyperopic subjects.

Serial number	Age (years)	Mean sphere of the spectacle correction (Dioptre)	Number with most positive vergence recognised	PBL through the hologram (Dioptre)
1	12	0.375	4	2.075
2	51	0.375	5	2.445
3	10	0.5	4	1.95
4	13	0.5	5	2.32
5	43	0.5	2	0.88
6	57	0.5	4	1.95
7	51	0.625	4	2.075
8	45	0.75	4	1.95
9	40	1	4	1.95
10	58	1.125	2	1.005
11	38	1.25	5	2.32
12	15	1.5	2	0.88
13	51	1.75	4	1.95
14	51	1.75	5	2.32
15	50	2.125	4	2.075
16	52	2.25	5	2.32
17	55	2.25	5	2.32
18	55	2.25	5	2.32
19	28	4.25	5	2.32

Mean: 1.97 D

Std dev: 0.50 D

Reproduced from (Nguyen et al., 2012), Table-3, P1177.

Table 8.6. Data obtained with the hologram for emmetropic subjects.

Serial number	Age (years)	Mean sphere of the spectacle correction (Dioptre)	Number with most positive vergence recognised	PBL through the hologram (Dioptre)
1	46	-0.25	4	1.95
2	49	-0.25	4	1.95
3	9	0	1	0.46
4	13	0	2	0.88
5	26	0	2	0.88
6	28	0	2	0.88
7	33	0	4	1.95
8	9	0	1	0.46
9	15	0	4	1.95
10	17	0	2	0.88
11	11	0.25	5	2.32
12	13	0.25	4	1.95
13	25	0.25	1	0.46
14	52	0.25	4	1.95
15	53	0.25	4	1.95
16	56	0.25	3	1.38
17	16	0.25	1	0.46
18	15	0.25	4	1.95

Mean: 1.37 D

Std dev: 0.68 D

Reproduced from (Nguyen et al., 2012), Table-4, P1178.

Discussion

8.4

The earlier studies with the multi-vergence hologram had indicated that the latent accommodation is not in play for hyperopic subjects viewing a multi-vergence target or a test chart at infinity in a hologram (Avudainayagam et al., 2007; Nguyen et al., 2013). Since it was found that progressive myopic subjects tended to respond like hyperopic subjects in viewing through the hologram in the current study, the author wonders if progressive myopic subjects are indeed individuals with hyperopia who have been initially misdiagnosed as having myopia due to their latent accommodation.

Figure 8.3. Simulation of the view through a hologram for a non-progressing myope.

Figure 8.4. Simulation of the view through a hologram for a progressing myope.

8.4.1 Accommodation during refraction and the phoropter

During the refraction process using the phoropter in the clinic, it is ostensibly assumed that subjects relax their accommodation through the fogging lenses. However, this may not always be the case, whereby positive lenses used for fogging might trigger the subject's accommodation (Reese & Fry, 1941; Ward & Charman, 1987). It follows then that this could result in an emmetropic or a low hyperopic subject being measured as a low myope, or, a more myopic error being measured for a low myope. Further, the coefficient of repeatability for subjective refraction performed by two different examiners on 86 subjects has been reported to be about 0.76 D in the literature (Bullimore, Fusaro, & Adams, 1998). Thus, the author believes that the refractive error measured using a phoropter could sometimes be in error especially in the diagnosis of low ametropia or when refraction was carried out without controlling accommodation appropriately. Accommodation whilst looking through the phoropter has also been previously reported (Borish, 2006).

8.4.2 Hologram for the classification of low ametropia

In my earlier study with the multi-vergence hologram (Chapter 5), the mean PBL of hyperopic subjects was greater than that of myopic subjects by about 0.9 D, the *P*-value for the mean difference was found to be 0.0000015 in a one-tailed t-test. Data from this earlier study has been reproduced in Tables 8.4, 8.5 and 8.6. Subjects with refractive error of ±0.25 D obtained using the phoropter were classified as emmetropic subjects in that study. However, if these low ametropes are classified into myopic and hyperopic subjects (i.e. the -0.25 D emmetropic subjects included with the myopic subjects and the +0.25 D emmetropic subjects included with the hyperopic subjects) the P-value for the mean difference falls to 0.00007 and the mean difference falls to 0.67 D. If instead, the PBL obtained with the hologram is used to classify the emmetropic subjects into myopic and hyperopic subjects (i.e. the emmetropic subjects whose PBL is less than 1.21 D as myopic subjects, and the emmetropic subjects whose PBL is greater than 1.21 D as hyperopic subjects), the P-value improves to 0.000000023 and the mean difference remains close to 0.9 D and is equal to 0.93 D. This suggests that the hologram may offer an improved way of identifying low ametropia as myopic or as hyperopic.

8.4.3 Latent accommodation and measured refractive error

Let us consider the following examples:

1) A +2 D hyperopic subject accommodating by +1 D when measured with the phoropter. This would result in a +1 D lens being prescribed for the +2 D hyperope, which implies +1 D of under correction.

2) A +0.5 D hyperopic subject accommodating by +1 D when measured with the phoropter. This would result in a −0.5 D lens being prescribed for the +0.5 D hyperope, which implies +1 D of under correction.

In the former case, a less positive lens is given to a hyperopic subject. When this subject lets go of his +1 D of accommodation, they will be left with +1 D of hyperopia. The image of a distant object will then be formed behind the retina, but the error will be only half as much as when he went for correction. This is not disastrous.

In the latter case, a negative lens is given to a hyperopic subject. When this subject lets go of his +1 D of accommodation, they will be left with +1 D of hyperopia due to the -0.5 D lens correction that is given to them. This leaves them with twice the error they had initially, giving a feedback signal that is twice as strong for eye growth. Being hyperopic, their eyes are inclined to grow longer. Maybe the latter hyperopic subject becomes a progressive myope?

The unknowns arising when refractive error is measured with a phoropter are the latent accommodation and the accommodation response of individual subjects to fogging lenses. A low hyperope stands a greater chance of receiving a negative correction due to his/her latent accommodation. Giving a negative correction to a hyperopic subject would enhance the negative blur, and negative blur is known to encourage eye growth (Wallman & Winawer, 2004). Providing a negative lens would upset the feedback loop in a hyperope and could eventually lead to a loss of control over the mechanism (Medina, 1987a, 1987b) that triggers eye growth. It thus seems possible that progressive myopia could result from hyperopic subjects being driven to myopia. Negative and positive lenses over the eyes have been shown to affect eye growth (Smith, 1998). The probability of the above error taking place is quite high considering that most children under 10 years of age are hyperopic and that the eye can grow up to the age of thirteen (Fledelius & Christensen, 1996). The fear of the child becoming a progressive myope and the parents’ concern for the child in this regard could promote more children to go for correction when it may not be needed (Donahue, 2004). Although emmetropisation occurs in early development, changes in eye growth could occur in young adults as well (McBrien & Adams, 1997).

The multi-vergence hologram could be used to test subjects of all age groups to check if they have vision like hyperopic people or vision like myopic people. It is possible that environmental factors could become a minor issue in myopia progression if low ametropia is identified correctly. The brain has a remarkable ability to cope with a wide range of lighting for example. On the contrary, the brain could be easily confused if an incorrect prescription, however small, is prescribed especially to developing children (Medina, 1987a; Smith, 1998). This view is supported by the fact that the literature is divided when it comes to environmental influences, but there is strong evidence on the progression of myopia and eye growth with incorrect lenses given to the eyes in the animal models (Morgan, Ohno-Matsui, & Saw, 2012).

Table 8.7. Correlation of age, pupil size, and refractive error with the PBL for progressive and non-progressive myopic subjects.

	Pearson correlation coefficient *r*, *P*-value of *r*	
	Progressive myopia	Non-progressive myopia
Age and PBL	0.57, 0.02	-0.16, 0.62
Pupil size and PBL	-0.52, 0.04	-0.37, 0.18
Refractive error and PBL	-0.63, 0.01	0.23, 0.47

8.4.4 Discussion on the results obtained with emmetropic subjects

The refractive error data obtained on the emmetropic subjects pursued in later years has been shown in Table 8.3. The first eight subjects responded with low PBL, and their refractive error was stable, confirming the high specificity of the test. The last three subjects responded with high PBL. One is a young subject (11-year-old), who was measured with 0 D refractive error in his first visit and who was developing into a progressive myope. The 50-year-old subject was a +0.25 D hyperope with a positive progression rate, indicating the emergence of latent hyperopia. The 30-year-old emmetrope could have been a latent hyperope based on his response to the hologram, and may possibly need reading glasses earlier than normal as it happened for one of the authors. It is possible that the 11-year-old subject was a latent hyperope who was diagnosed as a 0 D emmetrope in his first visit when he was also tested with the hologram. This subject was measured as having -1.875 D of myopia four years later. The author does not know when this subject was first prescribed a negative lens. Rendering a small negative lens correction to this subject between the two visits may possibly have induced progressive myopia.

8.4.5 Latent accommodation and progressive myopia

If a hyperopic person is diagnosed incorrectly as being myopic and prescribed a negative lens, then he will need to accommodate more in doing near tasks. He would also become wearier while doing near tasks, with the result being that the sharp image would frequently be formed behind the retina, signalling the brain for eye growth, and thus leading to progressive myopia. My earlier study indicated that the latent accommodation was responsible for the large PBL of hyperopic subjects. As some progressive myopic subjects showed large PBL like that of hyperopic subjects, it appears that progressive myopic subjects do have latent accommodation similar to hyperopic subjects. One could then expect some correlation of age, pupil size, and refractive error with the PBL for the progressive myopic subjects as accommodation is correlated to these factors. A significant medium correlation was obtained for progressive myopic subjects, but was not observed for non-progressive myopic subjects (Table 8.7) in this study.

The fact that atropine (which arrests the accommodative ability of a subject temporarily) serves as a deterrent to the development of progressive myopia (Song et al., 2011), lends support to the idea that progressive myopic subjects may have some latent accommodation similar to hyperopic subjects.

8.4.6 Classification of subjects based on PBL

It appears that the hologram is able to differentiate between subjects who have some latent accommodation and subjects who have no latent accommodation based on their PBL, irrespective of their refractive status. When I considered the data on the PBL that I obtained for various subjects in my earlier study (reproduced in Table 8.4, 8.5 and 8.6), and classified all the subjects based on the PBL into two groups, one having a high PBL (>1.21 D), and the other having a low PBL (<1.21 D), 33 subjects were found to have a high PBL, and 23 subjects were found to have a low PBL. The mean value of the high PBL was 1.98 D, with a standard deviation of 0.3 D. The mean value of the low PBL is 0.75 D, with a standard deviation of 0.2 D. The mean difference between the high PBL and the low PBL was 1.23 D with a *P*-value of zero (3.7×10-25). This difference perhaps gives a measure of the mean level of the latent accommodation when it is present, for subjects who show hyperope-like vision when tested with the hologram. These results also suggest that any given subject has a vision characterised by either low PBL (no latent accommodation) or high PBL (indicative of latent accommodation).

8.4.7 Progressive myopia and overcorrected myopic subjects

Progression rate was used to define progressive and non-progressive myopia in this study. As some of the myopic subjects classified as progressive myopic subjects by this definition did not show the hyperopic level of PBL in the test with the hologram, it may be that these myopic subjects were overcorrected myopic subjects who were rendered artificially hyperopic. These myopic subjects would then experience negative blur, which could eventually trigger progressive myopia. It is also possible that these myopic subjects would then be in the process of developing some latent accommodation due to the constant accommodation resulting from overcorrection. This might show up as high PBL in the test with the hologram when their refractive error goes beyond -1.5 D, a value close in magnitude to the suspected mean level of latent accommodation of 1.23 D that was obtained in the previous section. Visually inspecting Table 8.2 and Figure 8.4, one could see that all the progressive myopic subjects whose myopia was greater than -1.5 D responded with a high level of PBL. Therefore, it is possible that −1.5 D is close to the turning point for the progression of myopia for the overcorrected myopic subjects. Alternatively, even though these subjects show high progression rate, their refractive error in the later years may stabilise and they may turn out to be non-progressive myopic subjects. A retest with the hologram when the second refraction was carried out would have helped resolve this further, but is currently beyond the scope of this study. These observations and findings can be confirmed with further research.

The review of the literature showed that the cause of myopic progression is multi-factorial in nature, so there may be more than one cause for myopia development. Furthermore, there were many different classification systems for myopia (Chapter 1) and is indicative of a multifactorial cause for myopia development. Along a similar line of reasoning, the prevalence and progression in Asia is unusually high and probably has multiple causes. In this thesis (Chapters 3 and 4), it was already found that over-correction during refractive error measurements is a possibility. This is evident by the 'negative accommodation' found (Figure 4.3) as well as the comparison plot between subjective and holographic refraction (Figures 3.3 and 4.4). Hypothetically speaking, if indeed patients are over-corrected during subjective refraction, then they would have a higher PBL when measured with the MVT hologram. This study has shown that subjects with higher PBL were found to have progressive myopia, whereas subjects with lower PBL tended to have more stable refractive errors. This study suggests that perhaps over-correction is another cause for myopic progression in some subjects. This concept is not new, with animal studies showing that over-correction can lead to myopic progression (Irving, Callender, & Sivak, 1995; Pickett-Seltner, Sivak, & Pasternak, 1988; Schaeffel, Glasser, & Howland, 1988). Over-minusing a patient would worsen vision with negative blur, and negative blur could encourage ocular growth (Wallman & Winawer, 2004). It is therefore plausible to speculate that another reason for the high incident of myopia in Asia could be from over-minusing during subjective refraction.

In this study, the mean PBL for non-progressive myopic subjects was 0.55 D, with a standard deviation of 0.33 D. The mean PBL for progressive myopic subjects was 1.32 D, with a standard deviation of 0.75 D. Thus, the mean PBL for the progressive myopic subjects was 0.77 D greater than that for the non-progressive myopic subjects, and this difference was statistically significant in a one-tailed t-test, with a *P*-value of 0.0018 obtained for unequal variances. The chance of making a mistake and incorrectly rejecting the null hypothesis is therefore very remote (18 in 10000).

Although it is possible that the result observed may be a spurious correlation, further research and understanding of myopic progression is still valuable since the cause to myopic progression is still unknown.

8.4.8 Clinical use of the MVT hologram

A multi-vergence hologram can be used to test and predict myopic progression. Initial results indicate a sensitivity of 54% and a specificity of 100% for the test. In other words, subjects with a lower PBL had a more stable refractive status compared with subjects with a higher PBL. Although this property cannot be used to determine the nature of the subject’s ametropia, it can be useful as an extra test to help guide the clinician in the management of the patient’s ametropia. As discussed in Chapter 1, the control of accommodation is important in any refractive error determination, since any accommodation will result in an over-correction of myopia (and under-correction of hyperopia). This is undesirable because of possible asthenopic symptoms or eyestrain. Furthermore, subjective refraction can vary by as much as ±0.75 DS, making the use of subjective refraction alone unreliable for the monitoring of the patient’s refractive status. The MVT hologram has two useful features that can aid in the determination of the subject’s ametropia. The MVT hologram appears to be able to distinguish subjects into two distinct groups by the way subjects respond to the holographic target. The first group of subjects exhibit an involuntary accommodation that is associated with a more stable refractive error. The other group of subjects exhibit no involuntary accommodation, and this has been associated with myopic progression. Patients with low ametropia belonging to the progressing group may be monitored more closely for myopic progression. Appropriate guidelines and management could then be given to the patient to help better control the myopic progression. So hypothetically speaking, if a young hyperope or young myope belonged to the higher PBL group as measured with the hologram, this patient might be monitored more closely (every 6-12 months) rather than 2-3 years as currently is standard in Australia.

Another property of the MVT hologram that is useful in refractive error measurement is the difficulty in accommodation in the MVT hologram. If indeed subjects were accommodating during subjective refraction, then the final correction will render the subject artificially hyperopic. Hyperopic subjects looking into the MVT hologram will respond by reading very high up in the MVT. Even if there were some involuntary accommodation in the MVT hologram, their response would still put them into the higher PBL group. In either scenario, a high PBL will indicate further rechecks or an earlier re-examination and increases the chance to find and correct the mistake.

8.5

Conclusions

Currently, there is no test which can predict myopic progression in patients. There appears to be an association between the blur limit observed by subjects and myopic progression. In this sense, a multi-vergence hologram can be used to test and predict myopic progression. Initial results indicate a sensitivity of 54% and a specificity of 100% for the test.

My results suggest that progressive myopic subjects have some latent accommodation like hyperopic subjects and that progressive myopia could result from an incorrect diagnosis of hyperopia as myopia brought about by the play of latent accommodation. Progressive myopia could also result from overcorrection of low myopic subjects. Hence, progressive myopia may be preventable by a correct diagnosis of low hyperopia/myopia. My studies also show that the hologram can help diagnose low ametropia correctly. Based on my findings, I suggest that if a subject, diagnosed in the clinic using the phoropter as a low myope (-0.25 D to -1.00 D) responds as a true positive in the test with the hologram, then no corrective lenses be prescribed to the subject. Alternative preventive measures may include cycloplegic refraction and subsequent follow-up consultations. For higher myopic subjects, I suggest under correction when they respond as true positives. Under correction has been shown to slow down the progression of myopia (Phillips, 2005; Tokoro & Kabe, 1965). However, the literature is divided on the role of under correction in slowing down myopia progression (Ong, Grice, Held, Thorn, & Gwiazda, 1999). It is possible that the role of under correction in slowing down progressive myopia may prove to be significant if it is tried only on those classified as progressive myopic subjects by the test with the hologram.

It is interesting that the hologram is able to divide all of the subjects significantly into two distinct groups, irrespective of their refractive error: one having high PBL (indicative of subjects having latent accommodation) and the other having low PBL (indicative of subjects having no latent accommodation). Further research with the multi-vergence hologram would prove to be very useful in gaining an understanding of the nature of latent accommodation.

Summary and recommendations for future work

Chapter 9

The studies making up this thesis has made many new contributions to the scientific knowledge. New knowledge includes:

- The ability to use holograms for spherical refractive error with good agreement with current methods.
- Holographic refraction could inhibit accommodation when testing for spherical refractive error, thereby minimising the chance for over-correcting myopic subjects and under-correcting hyperopic subjects.
- A new classification system was developed for myopia by grouping myopic subjects according to their PBL. Myopic subjects in the higher PBL group had a greater mean progression rate than those in the lower PBL group.
- Discovery of a Mandelbaum-like effect from an MVT that was greater in myopic subjects. The effect was caused by near targets in the MVT.

The various studies in this thesis provided further insight into using coherent illumination for subjective refractive error measurements. Although the method is restricted to only simple ametropia, it provides credibility for further studies into the technology. The technology is probably not a replacement for existing methods, but offers an alternative where conventional methods may not be practical.

Summary

9.1

9.1.1 Holograms to test for spherical refractive error

The spherical refractive error was measured using a hologram of a multi-vergence target that consisted of test characters. The MVT in the original research (Avudainayagam et al., 2007) utilised a predictable numerical sequence with varying angular size at the eye that could have introduced bias into the refractive error measurements for high levels of ametropia. Despite these shortcomings, the research showed good potential since there was good agreement with conventional subjective methods and autorefraction.

Using holograms to measure refractive error is still a new technique, but has many attractive properties, such as being cheap to operate and manufacture, being long-lasting, offering the potential for battery operation and portability, and providing good agreement with the conventional refraction of using a refractor and logMAR chart.

Instead of using an MVT hologram to measure spherical refractive error, it was also possible to record a high-contrast logMAR hologram at optical infinity and measure refractive error using trial lenses. The results show good agreement between holographic refraction and conventional refraction, especially when results were adjusted for minor vergence differences between the two methods. Good agreement means that the two methods could be used interchangeably, and holography, again, shows good promise. However, if one was to consider the effects of chromatic differences in wavelength between the two methods, then subjects appear to be, on average, accommodating by a small amount (0.24 D) in the hologram of a logMAR chart (Chapter 3). Although the level of accommodation was low, it did raise the question about whether there was also a lead in accommodation when subjects were given ample viewing time of an MVT hologram.

Using a logMAR hologram to measure spherical refraction appears to be a viable method, since it also has good agreement with conventional methods. Whilst measurements require the use of trial lenses and are, therefore, more time consuming, the method has all the useful advantages of the MVT hologram discussed previously, including the inhibition of accommodation. Future studies should endeavour to determine the possibility of taking astigmatism measurements with this hologram. Unfortunately, visual acuity measurements with a hologram appears to be poor

A subsequent study showed that when subjects were permitted extended time to view the MVT hologram, there was also a tendency for subjects to have a lead in accommodation (0.68 D). Furthermore, the tendency was greater in myopic subjects than hyperopic subjects (MD = 0.65 D, $P < 0.02$). However, there was a significant age difference between the two groups that might have introduced bias into this result. Furthermore, measurements were taken from two different holograms that had very different optotype (letters versus integers) as well as possible different reconstruction efficiencies. Nonetheless, this study confirmed and consolidated a useful hologram exposure protocol for future holographic refractive error measurements.

9.1.2 Holograms to measure accommodation

An MVT hologram was shown to be able to measure the refractive state of the eye when subjects were accommodating to read a high-contrast near chart illuminated with polychromatic light (Avudainayagam et al., 2007). Furthermore, it was observed during this study and during refractive error measurements with a logMAR hologram (Chapter 3) that when given an accommodative stimulus to focus on, some subjects did not accommodate to clear the stimulus, even when the subject’s accommodative amplitude was adequate. An MVT hologram was subsequently used to investigate this phenomenon to reveal a general inhibition effect to accommodate in a hologram. This is in general agreement with accommodation studies using coherent illumination. However, coherent illumination is virtually non-existent in everyday life, so the inhibition of accommodation by coherent illumination light will, therefore, not pose much of an issue people’s daily activities. This study also showed that the use of a near holographic chart for near vision measurements will probably not be successful because of the apparent inhibition of accommodation, thus, rendering patients artificially presbyopic.

9.1.3 Myopia, hyperopia and the Mandelbaum-like effect

The research in this thesis is novel because it represents the first time where coherent illumination has been used with characters (letters, integers) in a hologram to probe human vision. Coherent illumination is foreign to our visual system and has some interesting side effects. An MVT hologram appears to not only inhibit the accommodation of subjects, but it causes a slight lead in accommodation as well. This involuntary accommodation was, on average, greater in myopic subjects than hyperopic subjects (Chapter 4), resulting in reduced PBLs in myopic subjects (Chapters 5 and 6). Initially, it was speculated that this observed difference was unique to the hologram. However, this was not found to be the case, since the difference was also reproducible in an optometer incorporating an MVT with a red laser diode as its illumination source (Chapter 7).

The Mandelbaum effect refers to an involuntary accommodation of the eye when presented with a conflicting visual system occupying the same visual space, such as a distant letter chart with an intervening screen (Mandelbaum, 1960; Owens, 1979). However, the effect can be highly variable between individuals (Leibowitz & Owens, 1978; Owens, 1979; Stark & Atchison, 1998). I was able to show that under coherent illumination, multiple targets at different vergences in close proximity to each other were enough to elicit an involuntary accommodation similar to the Mandelbaum effect. This Mandelbaum-like effect from the side-by-side targets was, on average, smaller in magnitude than the Mandelbaum effect that was caused by an intervening screen. Furthermore, it was shown on multiple occasions that myopic subjects had a greater involuntary accommodation than hyperopic subjects when asked to look at an MVT hologram (Chapters 5 and 6). By categorising subjects into either a myopic progressing group or a non-progressing group, it was discovered that there was a positive correlation between myopic progression and higher PBLs (Avudainayagam et al., 2015). In other words, it appears that the non-progressing group have a lower PBL, corresponding to a stronger Mandelbaum-like effect. Therefore, classifying myopic subjects into a high or low PBL group may prove useful at predicting myopic progression and future studies should look into it.

9.2 Study limitations and further studies

Cycloplegia was previously used in one of the studies but no significant level of latent hyperopia was found in subjects. However, this could be because only a few hyperopic subjects were cyclopleged and all had relatively low levels of hyperopia. The ability of the hologram to relax more accommodation in hyperopic subjects (and measure some latent hyperopia) could not be explored in this thesis. Up to date, measuring latent hyperopia requires the relaxation of the ciliary tone, which is only effectively achievable with cycloplegic eye drops. Although holographic refraction may not fully relax the ciliary tone to measure the full latent hyperopia, this may not be crucial since the full latent hyperopia may not be corrected anyway. If indeed the hologram could relax some of the eye’s ciliary tone and measure some latent hyperopia, as was observed in some subjects in a previous study (Appendix A). A study into how well subjects can tolerate the prescription from the holographic measurements would be useful. If successful, holographic refraction could be used to prescribe to correct some latent hyperopia to relieve asthenopic symptoms, without the need for cycloplegic refraction.

The logMAR hologram could have easily been recorded to show some dots or rings to measure astigmatism. As it stands, the holographic refraction is still limited to measuring simple ametropia. Future studies should investigate the performance of holographic refraction at measuring the astigmatism of the eye.

Good agreement was found when using the MVT hologram to measure spherical refractive error. However, the test targets were recorded at 0.50 D steps in the hologram. Although agreement was good enough for clinical purposes, accuracy could have been improved if trial lenses were used to shift vergences by 0.75 D and measurements retaken and averaged. It is possible to take multiple measurements using the one hologram by introducing trial lenses of varying magnitudes (such as +0.75 + 0.50 x n, where n is a whole number) in front of the eye. As long as the dioptric range of the MVT hologram is wide enough, accuracy should theoretically improve if more measurements were taken and then averaged. This is in contrast to subject refraction where the practitioner guides the refraction to reach only one endpoint. Unfortunately, this process was not carried out and tested in this thesis.

The hologram that was used for this thesis was a phase hologram made of photographic emulsions recorded with a ‘red’ laser light (633 nm). The maximal spectral sensitivity of the eye is not at this wavelength which might have resulted in the poor visual acuity measurements. Selecting a laser wavelength closer to the eye’s preferred wavelength (yellow) may improve visual acuity measurements. This was not tested in this thesis. Holograms could be used in future studies to investigate the effects of different wavelengths of laser light on the eye.

Although photographic emulsions have good enough resolution limits for vision testing purposes, its maximum diffraction efficiency is still lower than that of dichromated gelatin materials (maximum diffraction efficiency of 0.60 compared to 0.90 for dichromated gelatin). This material could have improved both visual acuity and refractive error measurements because of the improvement to perceived changes in target image. However, it was not used for studies in this thesis because a substantially higher powered laser or an impractical exposure time would be required. With lasers becoming more powerful in recent times, this limitation could be overcome in future studies.

Others future studies

Future studies should assess the potential to use holograms to measure the refractive state of the eye. The ‘flash on and off’ protocol, if performed in the dark, may possibly measure the dark focus of the eye (subjectively). There are elaborate methods to measure the dark focus subjectively involving the use of laser speckle on a rotating drum. However, an MVT hologram is faster, easier for subjects to comprehend and does not involve the use of lenses. If successful, it could be used to help diagnose for night myopia experienced by some patients.

There was an association between the PBL and myopic progression. It would be useful to perform a clinical study and to use cycloplegia to investigate this association further. A strong correlation may help researchers to further their understanding of myopic progression.

9.3

Conclusion

This thesis contributed to optometry with new knowledge about the human vision measured under coherent illumination. Until now, it was uncertain how the human visual system would respond to holographic constructs using coherent illumination. The research in this thesis has confirmed that holographic refraction for spherical subjective refraction is a viable alternative to conventional refraction. A hybrid method of a logMAR hologram and lenses also has good agreement with existing methods, and has potential to assess astigmatism for full (monocular) refractive error measurements. When allowed unrestricted time to observe the hologram, most subjects (especially myopic subjects) preferred to have a slight lead in accommodation when viewing the hologram reconstruction under 633 nm laser light. However, visual acuity measured in a hologram under 633 nm laser light was significantly worse than measured under white light probably because of laser speckle and the reduced sensitivity of the eye at this wavelength.

Appendices

Appendix A: Historical methods of subjective refraction

A1. Ready-made spectacles

According to Rosen (as cited by Bennett, 1986), spectacles probably first appeared around 1280, yet during that period, little was known about optics, the refraction of lenses or how the eye works. Spectacles would be selected (and not prescribed) through a process of trial and error, whereby ready-made spectacles were self-selected and a user would select the pair that best served the user's needs. This method of refractive error correction is not ideal since it corrects ametropia binocularly through trial and error, and is not specific to each eye. As a result, the ready-made spectacles could be over or under-correcting the user if he/she is anisometropic. Amazingly, this practice is still readily available in today's society where ready-made spectacles are sold in convenience stores or petrol stations as a temporary correction for presbyopia or hyperopia. However, this method is in existence in modern times not because of its accuracy to correct spherical ametropia, but rather because of its low cost and convenience to users. In Australia, ready-made spectacles are regulated by each State, and in New South Wales (NSW), the Optical Dispensers Amendment (Ready Made Spectacles) Regulation 1996 requires for the spectacles to:

- have lenses of equal power
- only correct presbyopia
- have optical powers between +1.00 D and 3.50 D inclusive
- have an appropriate label warning for users that it is not a substitute for an ocular examination (refraction).

Therefore, the use of ready-made spectacles (in NSW) cannot test for simple myopia and hyperopia greater than 3.50 D.

A2. Zahn’s polyspherical lenses

Johann Zahn (1641-1701) was probably the first to use a subjective test to measure the spherical refractive error of the human eye (rather than through trial and error with ready-made spectacles) (Bennett, 1986). Zahn developed a polyspherical lens (Figure 0.1) that was able to be used to perform spherical refraction monocularly. This is probably the earliest known refractor system. The lens by Zahn was made from a single piece of glass, which consisted of concentric zones of varying curvatures, and therefore, different optical powers. The lens came in two versions, a plano-concave (to test for myopia) and a plano-convex (to test for hyperopia). The design of a polyspherical lens was intended to provide the practitioner with six optical powers of varying strength (with the central zone being the lowest optical power). The procedure would be for the practitioner to bring one of the zones immediately in front of the patient’s eye (pupil). The polyspherical lens could then be moved up/down to successively bring each zone into view of the eye. It is unknown what powers were used by Zahn for the concentric zones, nor the dioptric step he employed between the zones. The method is simple, but many polyspherical lenses with varying optical powers would be necessary to adequately test a wide range of ametropia. This method, although in a slightly different form, is still in use in modern optometry. The lens rack often use with retinoscopy is, in principle, the same method but using many individual lenses of varying power rather than a single polyspherical lens. Furthermore, it is unknown how accurate the method is, but being the first refractor unit available, there was no other means to test its accuracy.

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Figure 0.1. An illustration of Johann Zahn’s
polyspherical lens (1985–86) as cited by Bennett (1986).

A3. The ophthalmic trial lens case

The use of trial lenses to determine the best correction for each individual eye was a significant advancement to the field of optometry. Instead of ready-made spectacles being selected by the user to aid their vision, trial lenses are used by a practitioner to prescribe a suitable correction for the patient. The idea is simple and appears to have come into use by three practitioners independently. According to Bennett (1986), in 1826, Du Bois described in a Prussian journal a set of trial lenses used in conjunction with an adjustable trial frame. The idea of a trial case was also designed by Professor Grubi in the 1830s and used at the St. Petersburgh Academy of Military Medicine. Finally, there was evidence of a Dr Fronmüller publishing an account of a trial lens set for his personal use in 1843.

Despite the advancements of this method, there are also some drawbacks. Firstly, it can be quite cumbersome and time-consuming to interchange between the different lens options (Grosvenor, 1996), and the trial frame loaded with trials lenses can be heavy when worn for long periods (Rabbetts, 2007). Historically, early trial lenses also suffered from incorrect effective power brought about by the addition of lenses with different lens thicknesses and form (Bennett, 1986). This issue was later resolved by Kellner with his patented ‘additive vertex power’ trial lens set (Kellner, 1918). However, if the patient’s line of gaze was not directed through the optical axes of the trial lenses, there would still be considerable oblique astigmatism and mean sphere errors (Rabbetts, 1984). This inherent flaw was more obvious for higher prescriptions and when checking for the near prescription (Bennett, 1986). To minimise these errors, it is now recommended to place the strongest spherical lens in the rear cell of the modern trial frame (Rabbetts, 2007).

Today, the trial lens set is a simple yet robust method that could be used by practitioners to determine the refractive error of patients. In combination with a trial frame, there are many adjustable features, such as vertex distance, lens centration control (centration distance and height), and pantoscopic tilt (Rabbetts, 2007). These features all aid to mimic the final spectacle prescribed from the trial frame and lenses combination. Even if trial frame refraction was not performed, it is still common practice to use the trial frame and trial lenses to verify the final lens prescription. The patient is able to move around in the trial frame and view objects of interest in a natural posture (e.g. reading a newspaper) to ensure good vision.

A4. Refracting units

It was only a matter of time before a faster method than using trial lenses was conceived to facilitate refractive error measurements. The refractor head (phoropter, phoro-optometer) was the next major advancement in the field of optometry. By housing the lenses (both spherical and cylindrical) into revolving discs, lenses could be presented quickly to the patient. Although there are various forms of refractor heads, Javal exhibited a refractor at a medical congress in Geneva (1877) that was remarkable because of the ability to change all the cylindrical axes simultaneously using a central gear wheel. There were two co-axial discs to hold spherical and cylindrical lenses separately. The disc holding the cylindrical lenses were stored in a toothed cell and could all be engaged simultaneously using a central gear wheel. This was a remarkable step forward because the axes of all the cylindrical lenses could then be dialled to any desired setting (Bennett, 1986), and this feature persists to modern day refractors. Although this refractor had two apertures to measure the two eyes, it could only refract one eye at a time due to the inability to adjust for different interpupillary distances (Figure 1.5). After the refraction of one eye was completed, the patient had to be moved across to begin refraction of the other eye.

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Figure 0.2. An illustration of Javal's refractor for monocular subjective refraction from Traité d'Optique by Sous, 1881 (Bennett, 1986).

A binocular refractor was thus developed in later years by a French ophthalmologist, Dr Giraud-Teulon that could be viewed as the prototype of the modern refractor head (Figure 1.6).

Figure 0.3. An illustration of a Giraud-Teulon's refractor head for binocular vision tests. Reproduced from the Encyclopédie Fracaise d'Ophtalmologie (Bennett, 1986).

Appendix B – Other types of media for holography

B1. Dichromated gelatin (DCG)

Is a grain-less and an ideal medium for volume hologram because of the materials' high capacity for refractive-index modulation, low absorption and low scattering. Holograms produced often have high resolving power and high image brightness (Hariharan, 1984). It has been known since 1830 that UV radiation or blue light can cause the gelatin molecules to cross-link if small traces of dichromate (such as $(NH_4)_2Cr_20_2$) are present (Bjelkhagen, 1993). Upon suitable light exposure, the hexavalent chromium ions (Cr^{6+}) are photo-induced to the trivalent chromium ions (Cr^{3+}) resulting in the localised cross-linking of the carboxylate group between neighbouring gelatin chains (Bjelkhagen, 1993, Hariharan, 1984). The exposed areas are therefore hardened and are less soluble than the unexposed area. Developing of these holograms involve the simple procedure of washing away the softer unexposed areas with warm water. However, a better outcome is obtained if the holograms were to be processed (Lin, 1969; Shankoff, 1968). With careful processing, the refractive-index modulation can be as high as 0.08, which is the highest amongst hologram materials known.

As already mentioned, the dichromate is sensitive to shorter wavelengths of light and to UV radiation. The spectral sensitivity of the dichromate gelatin drops rapidly to only a fifth of optimum at 514 nm, and to zero at 580 nm. To extend the sensitivity of the material to longer wavelengths, a He-Ne laser (633 nm) could still be used to record the hologram if the dichromated gelatin was sensitised with triphenylmethane dyes (Graube, 1973) or with methylene blue (Kubota & Ose, 1979).

Processing of the material is done in propanol baths starting with water-propanol solutions of high water content and gradually ending with pure propanol baths. The temperature of the bath could be used to control the quality and noise of the hologram, with warm baths yielding high index modulation (but with higher noise) while cold baths yield better uniformity holograms with less noise (Bjelkhagen, 1993).

B2. Silver-halide sensitised gelatin

It is possible to have the best of both worlds and combine the high sensitivity of silver halide photographic emulsions with the low scattering and high stability of dichromated gelatin. This is possible by exposing the silver halide photographic emulsion but processing the hologram to obtain a volume phase hologram made up solely of hardened gelatin (Pennington, Harper, & Laming, 1971). After processing, the hologram can have high efficiency of ~ 70% with sensitivity ten times higher than that of dichromated gelatin (Hariharan, 1984).

B3. Photoresists

These are light-sensitive organic films that can yield a hologram after proper exposure and development (Bartolini, 1977a). However, these holograms require a longer laser exposure time with lower diffraction efficiencies than other materials. They are still in use because of their ease to replicate in thermoplastic material. The material has a spectral sensitivity that is at maximum with UV radiation, with sensitivity dropping off dramatically with longer wavelengths (blue). It is therefore not a suitable material to record holograms to test human vision. Photoresist materials are often used as the master plates for embossed holograms (for display or security holograms) and for the manufacturing of holographic gratings (Bjelkhagen, 1993).

B4. Photopolymer

This organic material could be used to record holograms because the material could be activated with a photosensitiser to undergo photo-polymerization (or cross-linking) to exhibit thickness and refractive index variations within the material. The advantage of this photopolymer material is that it could yield a volume phase hologram with high diffraction efficiency that could be viewed immediately after exposure (dry processing). Furthermore, after light exposure, there is continual monomer diffusion into the zones of polymerisation when left in the dark resulting in slightly better refractive index modulation (Hariharan, 1984). A final exposure using regular light of uniform intensity is applied to complete the reaction and polymerise the remaining monomers. Nonetheless, refractive-index changes are still limited (Bjelkhagen, 1993) and together with its low sensitivity and relatively short shelf life, this material is not popular for general holography.

B5. Photochromics

Photochromic materials undergo a reversible change in colour when they are exposed to light. Many different types of organic photochromics have been studied previously and they were found to suffer from fatigue and limited life (Bartolini, 1977), rendering them not useful for holographic purposes. Inorganic photochromics could also be made to exhibit photochromism by doping the crystals with particular impurities (Duncan Jr & Staebler, 1977). These inorganic photochromics are grain-free so can have very high resolutions. Another advantage of this type of material is the ability to record multiple holograms into the one recording medium. Furthermore, they require no processing, and can be erased and reused almost indefinitely (Hariharan, 1984). However, photochromics suffer from low diffraction efficiency (<0.02) and low sensitivity. The more useful photochromic material is probably the photo-dichroic crystals (such as alkali halides). This material has the special property of an anisotropic absorption centre that has selective alignment when induced by linearly polarised light (Hariharan, 1984). Since only the direction of linear polarisation is changed, it is therefore possible to use a single laser for storage, readout and erasure (Casasent & Caimi, 1977).

B6. Photo-thermoplastics

It is also possible to record a hologram onto thermoplastic. To achieve, this, the thermoplastic is combined with a photoconductor and then charged to a very high voltage. When exposed to light, the photo-thermoplastic creates a spatially varying electrostatic field that can deform a heated (and therefore soft) thermoplastic. When left to cool, the thermoplastic hardens and the pattern of deformation is fixed (Urbach, 1977).

Photo-thermoplastics have good sensitivity across the visible spectrum, and can yield a thin phase hologram with good diffraction efficiencies. Furthermore, they can be quickly processed, erased and reused multiple times when used with a glass substrate. The most widely used photo-thermoplastic consists of a multilayer structure of a glass substrate, a thin transparent conducting layer (indium oxide), a photoconductor and a thermoplastic. Whilst in the dark, a corona device is used to sensitise the film by spraying positive ions to create a uniform electric field on the top layer of the photo-thermoplastic. This induces a uniform negative charge on the conductive layer on the substrate. When exposed to light, charged carriers are created wherever the light interacts with the photoconductor. These charge carriers partially neutralise the part of the charge that was deposited by the corona during the initial sensitising stage. The electric field is produced when the surface is 'recharged' a second time to deposit additional charges onto the surface resulting in a varying spatial electric field pattern. The thermoplastic is heated to near its softening point by applying an electric current through the conductor. Once the plastic is soft enough, local deformations start to appear in the spatially varying electric field, with greater deformations in areas of higher electric field intensity. When the plastic is left to cool, the thermoplastic hardens and the pattern of thickness variation is fixed into the material. To erase and reuse the hologram, the thermoplastic if flooded with light and is re-heated at a temperature that is slightly higher than that during hologram development (Pennington et al., 1971). The thickness variations of the hologram are lost as the thermoplastic softens. A blast of cold air could be applied to return the photo-thermoplastic back to room temperature to be re-used. Instead of softening the thermoplastic with heat, it also possible to soften the plastic using solvent vapours that has the beneficial effect of increased sensitivity and lower noise (Saito, Imamura, Honda, & Tsujiuchi, 1980). Greater sensitivity can also be achieved by using double-layer and triple-layer photoconductor systems (Saito, Imamura, Honda, & Tsujiuchi, 1981).

One major disadvantage of this type of material is the limited life of the thermoplastic layer. Ozone produced during the charging process degrades the material, and limits it useful life to 10-100 process and erase cycles. Protecting the system from ozone can extend its useful life to over 300 cycles whilst maintaining good diffraction efficiency.

B7. Photorefractive crystals

When these crystals are exposed to light, the region being exposed can free trapped electrons. These electrons often migrate through the crystal lattice and become trapped in an adjacent unexposed area of the crystal. A spatially varying electric field then exists in the crystal, resulting in the modulation of the refractive index (through the electro-optic effect) and the formation of a phase hologram. This hologram can be erased by uniformly illuminating the crystal with light, and can theoretically be recycled indefinitely (Hariharan, 1984).

Table of recording materials for holography

Material	Reusable	Processing	Type of hologram	Spectral sensitivity (nm)	Max. diffraction grating efficiency
Photographic emulsion	No	Wet chemical	Amplitude phase	400-700	0.05 0.60
Dichromatic gelatin	No	Wet chemical	Phase	350-580	0.90
Photoresists	No	Wet chemical	Phase	Uv-500	0.30
Photopolymers	Yes	Post exposure	Phase	Uv-650	0.90
Photochromics	Yes	None	Amplitude	300-700	0.02
Photo-thermoplastics	Yes	Charge and heat	Phase	400-650	0.30
Photorefractive	yes	none	Phase	350-~550	~0.20

B8. Additional materials

Although the following materials can be used for holography, there are few practical applications reported so far:

- Chalcogenide glass
- Ferroelectric-photoconductors
- Liquid crystals
- Magneto-optic films
- Metal and organic-dye ablative films
- Photochromic and photo-dichroic materials
- Transparent electrophotographic films
- Light-harvesting protein (bacteria rhodopsin).

Appendix C: Paper written during candidature but not forming part of the thesis (supplied with permission from publisher).

Performance of the holographic multivergence target in the subjective measurement of spherical refractive error and amplitude of accommodation of the human eye

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We recently suggested the use of a holographic multivergence target to measure the spherical refractive error and the amplitude of accommodation of the human eye [K. V. Avudainayagam and C. S. Avudainayagam, Opt. Lett. 28, 123 (2003)]. In this paper we report the performance of the holographic target in measuring real eyes. The holographic technique compared well with subjective refraction and autorefraction in the measurement of spherical refractive error. The performance of the holographic technique in measuring the amplitude of accommodation was similar to that of the minus lens to blur method and that of the push-up method. These results promote holography as a promising technique for testing human vision. © 2007 Optical Society of America

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1. INTRODUCTION

Currently, subjective refraction using a refractor is considered to be the gold standard in measuring the refractive error of the human eye [1]. However, the measuring instrument is expensive and the procedure is elaborate. Similarly, the push-up (PU) method and the minus lens to blur (MLB) method are widely used to measure the amplitude of accommodation of a subject [2]. In the PU method a subject is made to move a target closer and closer until it begins to blur. As the target is brought closer it subtends a larger angle at the eye and is easier to recognize. Hence this method yields a higher value for the amplitude of accommodation of a subject than other methods [3]. In the MLB method a subject is made to see a target through a series of negative lenses of increasing power placed sequentially in front of his/her eye. The power of the negative lens for which the target just begins to blur determines the amplitude of accommodation of the subject. Thus the subject has to look through a series of lenses before arriving at the endpoint. Recently, we suggested the use of a holographic multi-vergence target to measure both the spherical refractive error and the amplitude of accommodation of the human eye [4]. The holographic target offers a very simple means of measuring the spherical refractive error and the amplitude of accommodation. We now report the performance of such a target in measuring the spherical refractive error and the amplitude of accommodation of 20 young non-astigmatic sub jects. The results are very encouraging, and we present the same here.

2. MEASUREMENT METHODS

A. Spherical Refractive Error

A total of 22 young normal subjects aged between 11 and

33 years were tested. The best corrected visual acuity of these subjects was 6 / 6, and their spherical refractive error was in the range of −5.0 to + 2.5 D with astigmatism less than 0.50 D. The range for the spherical refractive error was decided by the dioptric range of the holographic multi-vergence target used. The spherical refractive error R_x was measured using subjective refraction, autorefraction, and holographic refraction. Subjective refraction was done using the refractor. One clinician performed the refraction under mesopic conditions. The Bailey–Lovie letter chart with high contrast was used as the target. The criterion used for the subjective endpoint was maximum plus for best monocular visual acuity. Spherical lenses in

0.25 D steps were used to determine the endpoint. Objective refraction was done by a different clinician using the HOYA HRK200 autorefractor. An average of three readings was taken for each subject with the autorefractor. To perform holographic refraction, a multi-vergence target was used in the form of a hologram. The hologram used is a phase hologram that resembles a transparent glass plate. Details of the design, fabrication, and illumination of the holographic multi-vergence target when in use can be found in our earlier publication [4].

The hologram contains the images of 16 integer numbers from −10 to +5 placed at various distances from it. The hologram was recorded using a specially designed three-dimensional object and an imaging lens.

The arrangement of the specially designed three-dimensional object, the imaging lens, and the holographic plate used to record the hologram is shown in Fig. 1. The three dimensional object shown consists of printed inverted numbers (about 0.75 mm in size) kept at different distances from a 20 D lens. The lens would form erect images of these numbers at various distances from it. The image forming wavefronts emerging from the lens are recorded in the hologram using a plane reference wave. For testing the refractive error of a subject, the hologram is illuminated by a plane reference wave traveling in the opposite direction. The phase conjugate of the recorded wavefronts is then recreated (see Fig. 2). An aperture of diameter 10 mm was placed at the lens while recording. During reconstruction the phase-conjugated wavefronts pass through the region where the aperture was. The observer’s eye is made to coincide with this region. When the subject places his/her eye at the location where the lens was with respect to the hologram during recording, the recreated phase-conjugated wavefronts reach his/her eye. The subject will therefore see various numbers placed at different distances from his/her eye. The average angular size of the numbers seen through the hologram is 47’, which is much larger than the threshold size of 5 required by a normal subject. The image vergences of these numbers correspond to a range of −5.0 to + 2.5 D at this location. As the object was hand fabricated with the help of a microscope, the error in the vergences of the number targets due to error in positioning of the sticks after fabrication was within ±0.10 D. The dioptric separation between two consecutive images is 0.50 D. The numbers used in the three-dimensional target correspond to twice the vergences of the corresponding images in the view through the hologram. For example, the light reaching the subject's eye from the number −6 will have a vergence of −3 D at the subject's eye. The subject is asked to identify the most positive number that he/she can see clearly. This is the number seen by the subject when his/ her eye is in the most relaxed state of accommodation. Half the value of the most positive number seen by the subject gives the subject's spherical refractive error. To ensure that the subject's eye is fully relaxed while taking the measurement, the subject is asked to look at a distant illiterate-E through the hologram when it is not illuminated. As the subject is looking at this target, the plane reference beam that is used to illuminate the hologram is switched on. The reference beam power used depends on the diffraction efficiency of the hologram. The

Fig. 1. Interference between the object wave (image forming wavefronts emerging from the lens) and the plane reference wave is recorded on the holographic plate.

Fig. 2. When the hologram is illuminated by the reverse traveling reference wave the phase conjugated object wave is recreated. For testing the lens is removed and the eye is placed at the location of the lens.

brightness of the re constructed image and the room lighting corresponded to mesopic conditions and matched the testing conditions used for subjective refraction. When the reference beam is switched on, the subject will see some numbers. He/she is asked to identify the most positive number N_{max} that he/ she can see clearly. This value is noted, and the reference wave is blocked. The reference beam is flashed briefly again for 10–15 s after an interval of about 30 s to 1 min to take the next reading. An average of three readings is used to obtain N_{max} (sometimes, a fourth reading was taken at the request of the subject). R_x is then equal to $N_{\max} / 2$. Thus the procedure to measure the spherical refractive error of a subject by the holographic method is extremely simple and quick. However, as the subjects who participated in the study were young subjects, when asked to call out the most positive number that was seen clearly, their answer was often different from one reading to another. As mentioned earlier the average of different readings obtained for each subject was used in the analysis. If the most positive number out of the different readings for each subject is used in the analysis instead, a hyperopic shift of about 0.3 D is observed compared with the results obtained by subjective refraction using the refractor. This shift may be associated with the chromatic aberration of the subjects for the red light that was used to illuminate the hologram. This shift is not obtained when the average of different readings for each subject in the holographic method is used to calculate the refractive error for the subject. This could be partly due to the tendency of the subject to accommodate and partly due to the subjective nature of the test.

B. Amplitude of Accommodation

The holographic multi-vergence target provides the subject simultaneously with images of targets located at different distances from the eye. These images have been designed to subtend more or less the same angle at the eye. When a subject looks through the hologram, the range of numbers that he/she can see clearly was expected to de pend on the amplitude of accommodation Amp of the subject. However, in trying to measure the amplitude of accommodation using this target we found that the holographic target did not sufficiently stimulate the accommodation of young subjects. Most of the young subjects could see only about 6 to 8 numbers out of the 16 numbers recorded in the hologram, which corresponds to an accommodation range of 3 to 4 D. Even those who could normally exercise their will and accommodate could exercise only a fraction of their accommodation when viewing through the hologram. When the subject was provided with a near reading chart at a close distance behind the hologram, he/she was able to accommodate and see the numbers corresponding to closer distances in the hologram. We therefore introduced a near target in front of the subject’s eye to stimulate his/her accommodation. Further, as the maximum range measurable by the hologram was limited to 7.5 D, a single negative lens of appropriate power was placed in the spectacle plane of the subject to measure the full amplitude of accommodation in one step. The power of the negative lens was chosen de pending on the expected amplitude of accommodation for the subject. The expected amplitude of accommodation for a subject was determined using Donder’s table [5,6].

Thus to measure the amplitude of accommodation of a subject monocularly, the right eye of the subject is occluded and a near letter chart having a few letters is placed at a distance of 40 cm from the subject’s left eye. A negative spherical lens of power $R_x - 2/3$ Amp is placed at the spectacle plane of the subject, where R_x is the spectacle correction of the subject and Amp for the subject is determined using Donder’s table. The subject is asked to look through the negative lens and the unilluminated hologram at the near letter chart. While the subject is looking at the chart the hologram is illuminated by the reference beam. The subject immediately sees some numbers. The most negative number seen by the subject, N_{min}, is noted, as this is the number that is seen with maximum accommodation by the subject. The amplitude of accommodation of the subject is then obtained from $2/3$ Amp $- N_{\min}/2$. This method is simpler and easier than the PU and MLB methods.

3. RESULTS

A. Spherical Refractive Error

Subjective refraction is considered the gold standard in refraction. Therefore, we compared the results obtained by the holographic method and those obtained by autorefraction against the results obtained by subjective refraction. We repeated all the measurements made using the holographic method twice with about half an hour break in between to test its repeatability. We analysed the results following Bland and Altman [7].

Out of 22 subjects who took part in the study, 17 were myopic and 5 were hyperopic. The data

obtained for these subjects by the three methods are given in Table 1.

As per subjective refraction the hyperopic subjects we measured had a hyperopia of ≤ 0.75 D. But, when measured by the holographic method two of these subjects revealed a hyperopia of 2.5 D (the highest degree of hyperopia measurable with our target was 2.5 D). We are inclined to believe therefore that the holographic multivergence target has the potential to measure the true level of hyperopia. This is possibly because the human visual system is accustomed to seeing everyday targets under incoherent white light illumination, whereas the hologram is viewed under coherent monochromatic illumination. This observation and reasoning need to be tested and researched further on a larger population of hyperopic people of all age groups. I have excluded the data obtained for these two subjects in the statistical analysis of the results obtained.

Table 1. Spherical Refractive Error Measured by Holographic Refraction, Subjective Refraction, and Autorefraction for 22 Subjects Aged between 11 and 33 Years

Subject	H1	H2	H1 and H2 Average	Auto refraction	Subjective Refraction
1	−0.13	−0.38	−0.25	−0.83	−0.25
2	−1.50	−1.50	−1.50	−1.63	−1.00
3	−4.17	−4.50	−4.33	−5.04	−4.50
4	+0.67	+0.17	+0.42	+0.42	+0.75
5	−0.50	−0.13	−0.31	−0.75	−0.25
6	0.00	−0.13	−0.06	−0.13	+0.75
7	+0.17	−0.25	−0.04	−0.08	+0.25
8	−3.13	−2.75	−2.94	−3.50	−3.50
9	−5.00	−5.00	−5.00	−5.83	−4.75
10	−1.12	−1.83	−1.48	−2.08	−1.75
11	−3.33	−3.75	−3.54	−4.79	−3.75
12	−0.50	−0.50	−0.50	−1.04	−0.25
13	−0.25	−0.38	−0.31	−0.67	0.00
14	−2.00	−2.38	−2.19	−3.08	−1.50
15	−0.63	+0.13	−0.25	−0.05	0.00
16	−3.67	−4.17	−3.92	−4.83	−4.25
17	−3.50	−3.88	−3.69	−5.04	−4.25
18	+0.50	−0.10	+0.20	−0.25	−0.25
19	−0.25	−0.25	−0.25	−1.00	−0.75
20	−1.00	−1.13	−1.06	−0.88	-1.00
21[α]	2.50	≥2.50	≥2.50	−0.08	+0.75
22[α]	≥2.50	≥2.50	≥2.50	+0.67	+0.75

[a] Data omitted in the analysis

The average of two measurements of spherical refractive error (H1 and H2) obtained for each subject by the holographic method is compared against the measurements obtained by subjective refraction in Fig. 3(a). The solid line is the line of equality. The Pearson correlation coefficient obtained for the two methods is 0.98. The mean versus difference plot is shown in Fig. 3(b). The dashed lines show the limits of agreement. The mean difference between the two methods is −0.04 D. The agreement between the two methods is summarized by the mean difference and the standard deviation of the differences. The mean difference $\bar{d}$ indicates the bias if any of our method against the old method. If there is a consistent bias, we can adjust for it by subtracting the mean difference from our method. In our study the mean difference between the results obtained by holographic refraction and subjective refraction is negligible. The standard deviation of the differences (SD) is used to tell whether our method is clinically acceptable or not. If $\bar{d} - 2$ SD to $\bar{d} + 2$ SD is clinically acceptable, then our method is acceptable. The values given by $\bar{d} - 2$ SD and $\bar{d} + 2$ SD are called the limits of agreement for the sample. The limits of agreement obtained for the sample in our study are −0.83 to + 0.76 D. A study on subjective refraction carried out on 86 subjects by two independent practitioners showed the limits of agreement for the sample to be −0.90 to + 0.65 D (see page 110 of [2]). Comparison of our results with those obtained for subjective refraction shows that holographic re fraction is clinically acceptable. The limits of agreement obtained for a sample are only estimates for the whole population. The 95% confidence interval for a measured value from the population is given by $\pm t\surd(\mathrm{SD}_2/n)$, where the value of t is obtained from the two-tailed student-t distribution with $n - 1$ degrees of freedom. This was calculated to be ±0.19 D from our study. This means that if we measure any subject from the population by the holographic method, then we can say with 95% confidence that the measured value will be within ±0.19 D of the value obtained by subjective refraction using the refractor. The coefficient of accuracy between the two methods is given by 1.96 times the SD of the differences, and this was obtained as 0.78 D in our study.

Fig. 3. (a) Plot of spherical refractive error obtained by holographic refraction against subjective refraction. (b) Difference versus mean plot for the measurements obtained by holographic and subjective refraction.

Figure 4(a) is a comparison plot of the results obtained by autorefraction against those obtained by subjective re fraction. The Pearson correlation coefficient here too is 0.98. Figure 4(b) is the mean versus difference plot obtained for the two methods. The mean difference between the two methods is −0.54 D. The 95% confidence interval for a measured value from the population is again ±0.19 D. The limits of agreement for the sample are −1.36 to + 0.28 D. The coefficient of accuracy is 0.8 D. The results obtained by the holographic technique are as good as those obtained by the HOYA HRK2000 autorefractor.

The results obtained for the repeatability of the holographic method are presented in Figs. 5(a) and 5(b). Figure 5(a) is a plot of the first set of measurements obtained by holography versus the second set. The Pearson correlation coefficient obtained is 0.98. Figure 5(b) is the mean versus difference plot for the data.

The mean difference between the two sets of measurements is 0.17 D. The 95% confidence interval for a measured value from the population is ±0.17 D. The limits of agreement for the sample are −0.87 to + 0.54 D. The coefficient of repeatability is given by 1.96 times the standard deviation of the differences between the test and retest values. This was obtained to be 0.69 D in our study. The coefficient of repeat ability for subjective refraction performed by two different examiners on 86 subjects was 0.76 in [2] (see page 110). A smaller value indicates better performance. The results indicate that our holographic technique has a good potential to be an alternative means of determining the spherical refractive error of a subject.

To refine the measurements obtainable by holography a +0.25 D and a −0.25 D lens may be introduced alternately

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Fig. 4. (a) Plot of spherical refractive error obtained by autorefraction against subjective refraction. (b) Difference versus mean plot for the measurements obtained by autorefraction and subjective refraction.

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Fig. 5. (a) Plot of the first set of measurements of spherical refractive error obtained using the holographic target against the second set of measurements. (b) Difference versus mean plot for the two sets of measurements obtained using the holographic target.

Table 2. Data Obtained for the Amplitude of Accommodation Using the Holographic Target, MLB, and PU Methods

Subject	H1	H2	H1 and H2 Average	MLB	PU
1	7.38	7.13	7.26	9.25	11.11
2	6.50	8.50	7.50	10.50	9.50
3	7.08	8.25	7.67	13.00	14.17
4	6.92	6.17	6.55	9.25	11.27
5	8.50	9.13	8.81	10.25	9.30
6	8.25	6.125	7.19	9.50	10.00
7	8.17	7.75	7.96	8.75	8.25
8	9.38	9.25	9.33	8.00	13.50
9	7.50	9.00	8.25	11.25	13.00
10	8.88	8.67	8.78	10.5	7.25
11	8.67	9.25	8.96	10.25	12.00
12	8.00	5.50	6.75	7.50	7.75
13	7.75	6.63	7.19	7.50	11.75
14	7.25	8.89	8.06	6.75	9.00
15	7.89	7.13	7.51	7.75	11.50

16	8.83	9.58	9.21	10.00	12.00
17	10.00	9.63	9.81	8.00	12.50
18	9.50	9.40	9.45	9.75	11.11
19	7.25	7.25	7.25	8.75	10.00
20	5.50	4.38	4.94	7.75	8.71

in the path of the reference beam and the spherical refractive error measured each time. This will shift the vergences of the images viewed through the hologram by ±0.25 D. The average value of the spherical refractive error thus obtained can improve the accuracy of measurements to ±0.125 D. Note that to shift the image vergences by ±0.25 D, the ±0.25 D lenses may be introduced in the path of the reference beam rather than in front of the subject's eye. This is a further advantage of the holographic technique. The hologram contains the record of the object and the reference waves. When illuminated by the reference wave, the object wave emerges from the hologram (the reference wave is subtracted from the record). Similarly, when it is illuminated by the object wave, the reference wave emerges from the hologram (the object wave is subtracted from the record). Because we are using a reverse-traveling wave in our experimental arrangement, when spherical power is added to the reference wave the phase conjugate of the spherical power is subtracted from the emerging phase-conjugated object wavefronts. This is equivalent to adding the same spherical power in front of the subject's eye.

B. Amplitude of Accommodation

The PU and MLB methods are two standard methods used to measure the amplitude of accommodation Amp of a subject. We measured the amplitude of accommodation of the subjects by both these methods and by the holographic method. We compared the performance of the PU method against the MLB method and found that the results obtained by these two methods have a poor correlation. The PU method is generally known to give a higher value for the amplitude of accommodation than the MLB method for a subject. The holographic method gave values less than the MLB method. We first compare the Amp obtained by the MLB method with the values obtained by the PU method. We then compare Amp obtained by the holographic method with the values obtained by the MLB and PU methods.

The data obtained for the amplitude of accommodation by the holographic, MLB, and PU methods are given in Table 2. Figure 6(a) compares the results obtained by the PU method against that obtained by the MLB method. The Pearson correlation coefficient for the two methods is poor (0.32). The mean versus difference plot for the data obtained by these two methods is shown in Fig. 6(b). The mean difference between the two methods is 1.47 D. The 95% confidence interval for a measured value from the population is ±0.94 D.

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Fig. 6. (a) Plot of the amplitude of accommodation obtained by the PU method against those obtained by the MLB method. (b) Difference versus mean plot for the measurements obtained by the PU and MLB methods.

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Fig. 7. (a) Plot of the amplitude of accommodation obtained using the holographic target against those obtained by the MLB method. (b) Difference versus mean plot for the measurements obtained by the holographic and MLB methods.

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Fig. 8. (a) Plot of the amplitude of accommodation obtained using the holographic target against the amplitudes obtained by the PU method. (b) Difference versus mean plot for the measurements obtained by the holographic and PU methods.

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Fig. 9. (a) Plot of the first set of measurements of the amplitude of accommodation obtained using the holographic target against the second set of measurements. (b) Difference versus mean plot for the two sets of measurements obtained using the holographic target.

Figure 7(a) compares the results obtained by the holographic method against those obtained by the MLB method. The Pearson correlation coefficient is 0.23. The mean versus difference plot for the measurements obtained by these two methods is shown in Fig. 7(b). The mean difference between the two methods is −1.29 D. The 95% confidence interval for a measured value from the population is ±0.78 D. While the results obtained by the PU method show a positive bias in comparison with the MLB method, the results obtained using the holographic method show a negative bias in comparison with the MLB method.

Figure 8(a) compares the results obtained by the holographic method against those obtained by the PU method. The Pearson correlation coefficient is 0.34. The mean versus difference plot for the measurements obtained by these two methods is shown in Fig. 8(b). The mean difference between the two methods is −2.76 D. The 95% confidence interval for a measured value from the population is ±0.87 D. Even though the bias between the holographic and PU methods is larger than the bias between the holographic and MLB methods, the results obtained by holographic method correlate better with the PU method with a Pearson correlation coefficient of 0.34. In this study we have used a negative lens of power equal to 2/3 of the expected Amp predicted by Donder's table, at the spectacle plane of the subject. Use of a negative lens of power equal to the expected Amp instead may yield higher estimates of Amp by the holographic method than those obtained here.

The standard deviation of the differences between the MLB method and the PU method is ±2.01 D. The standard deviation of the differences between the holographic method and the MLB method is ±1.67 D. The standard deviation of the differences between the holographic method and the PU method is ±1.86 D. Thus, of the three methods studied, the holographic method compares better with the MLB method and the PU method than the MLB and PU do with each other.

The age group of the subjects we measured was narrow and in the range of 17 to 24 years. The fluctuation in the measured values of accommodation within this age group is least for the holographic method and most for the PU method. The standard deviation of the measured values for this age group is 1.19 D for holography, 1.53 D for MLB, and 1.95 D for the PU method. The mean value of the accommodation obtained for this age group is 7.92 D by holography, 9.21 D by MLB, and 10.68 D by the PU method. This corresponds to a 15% variation from the mean for the holographic method, 16.6% variation from the mean for the MLB method, and 18.3% variation from the mean for the PU method.

To check repeatability, two measurements of the amplitude of accommodation were carried out on each subject. Figure 9(a) is a plot of the first set of measurements against the second set of measurements for the amplitude of accommodation obtained using the holographic target. The Pearson correlation coefficient is 0.64. Figure 9(b) is the mean versus difference plot for the data. The mean difference between the two sets of measurements is

−0.08 D. The 95% confidence interval for a measured value from the population is ±0.54 D.

4. CONCLUSIONS

The performance of a technique that makes use of a hologram to measure the spherical refractive error of the human eye has been compared with subjective refraction and autorefraction. The method compares well with existing methods in the measurement of spherical refractive error. The measurement method is very simple. Further, the holograms are portable and inexpensive. A measure of the amplitude of accommodation is important while pre scribing Adds to presbyopic subjects for doing near work ("Add" is the unit for the additional power over and above the distance correction). An amplitude measurement is also important while testing the vision of small children. Subjects belonging to these age groups will benefit from a simple measurement procedure.

The holographic technique is an attractive alternative to existing methods for the measurement of amplitude of accommodation. The holographic method presented here can be extended to measure astigmatism as well. We are currently investigating the feasibility of such an extension [8]. The holographic method reported here will be particularly useful in re mote areas and regions where standard facilities and the number of optometrists are limited.

REFERENCES

1. W. J. Benjamin, *Borish’s Clinical Refraction* (Saunders, 1998).

2. R. B. Rabbetts, *Bennett and Rabbetts’ Clinical Visual Optics* (Butterworth Heinemann, 1998).

3. M. Rosenfield and A. S. Cohen, “Repeatability of clinical measurements of the amplitude of accommodation,” Ophthalmic Physiol. Opt. 16, 247–249 (1996).

4. K. V. Avudainayagam and C. S. Avudainayagam, “Holographic multivergence target for subjective measurement of the spherical power error of the human eye,” Opt. Lett. 28, 123–125 (2003).

5. F. C. Donders, *Accommodation and Refraction of the Eye* (New Sydenham Society, 1864).

6. A. Duane, “Normal values of the accommodation of all ages,” J. Am. Med. Assoc. 59, 1010–1013 (1912).

7. J. M. Bland and D. J. Altman, “Statistical methods for assessing agreement between two methods of clinical measurement,” Lancet 1, 307–310 (1986).

8. K. V. Avudainayagam and C. S. Avudainayagam, “Holographic multivergence target for subjective measurement of the astigmatic error of the human eye,” Opt. Lett. 32, 1926–1928 (2007).

Appendix D: Conference papers

During my PhD Candidature, I was able to present my findings at two international conference with details below:

D1. International conference in optics held in Sydney in 2008 (International Commission for Optics ICO – 2008 Congress, Sydney, Australia, July 2008).

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D2. 12th Scientific meeting in Optometry in New Zealand in 2008

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D3. Frontiers in Optics conference held in Rochester, NY, USA in 2010 (Accepted but could not attend the conference)

Holographic LogMAR Chart at Infinity to Test Vision

Nicholas Nguyen,[1] Chitralekha S Avudainayagam, and Kodikullam V Avudainayagam*

School of Optometry and Vision Science, University of New South Wales, Anzac Pde, Kensington, NSW 2207, Australia

In this paper we report the recording and use of a holographic LogMAR chart imaged at infinity to measure the visual acuity (VA) of various distance corrected subjects. We also used this chart to study the role of illumination in the measurement of the positive blur that can be tolerated by subjects in recognising large high contrast letters through a hologram. Our results seem to indicate that the multivergence nature of the targets used in a hologram rather than the coherency or wavelength of the illumination is responsible for the differences that we observed in the vision of hyperopic and myopic subjects in our earlier study. Our results also suggest that a '36-meter' letter size is optimum when used in a hologram for the purpose of refraction as visual acuity for all the subjects is worse while seeing through the hologram due to coherent illumination. Once calibrated and standardised, a logMAR hologram may serve as a portable and compact open field target to test visual acuity.

OCIS Codes: 090.2890,330.1070

It has been shown that a suitable three dimensional multivergence target can be recorded in a single hologram and used to measure the refractive error of the human eye [1-3]. In viewing through this hologram which is illuminated with light from a low power He-Ne laser, subjects see an array of letters placed at various distances from the eye, both in front of the eye and behind the eye (as virtual objects). The letter with the most positive vergence that is seen clearly by the subject is used to determine the subject's refractive error. In a subsequent study, distance (spectacle) corrected subjects were asked to view through a similar hologram. In looking through the hologram with the distance correction in place the wavefront reaching the eye for the virtual letters correspond to letters with positive blur. The letter with most positive blur that is recognized by the subject was investigated for various subjects [4]. We found that there is a difference in the limits of positive blur tolerated by distance corrected hyperopic subjects and distance corrected myopic subjects in recognizing large (60-metre) high contrast holographic letters. Distance corrected hyperopic and myopic subjects show no difference in their ability to recognize large test letters under positive blur that is introduced with lenses while viewing letters on a standard logMAR chart under white light illumination [5-6]. To find if the observed difference between the vision of hyperopic and myopic subjects while viewing through the hologram was due to the monochromatic and coherent nature of the illumination that was used, we have now fabricated a LogMAR chart at a single distance of infinity in a hologram. We used this hologram to test the vision of various subjects using positive lenses to blur their vision.

To test the visual acuity of subjects in fine steps a LogMAR chart placed at 6 metre distance is normally used under white light illumination. It would be ideal if a target could be provided at true infinity. While such a chart could be provided in an optometer, the optometer is known to trigger proximal accommodation. We realized that if a hologram of a logMAR chart is recorded at true infinity, then such a hologram would provide an open field view of the test chart at infinity. However as light from a laser is used to illuminate the hologram, the visual acuity would be affected by the coherence and monochromaticity of the illumination, as the performance of any imaging system is known to be worse under coherent monochromatic illumination than it is under incoherent white light illumination. We therefore conducted experiments to determine the visual acuity using logMAR charts under various illuminations. In this paper we report the interesting results that were obtained from this study.

A schematic diagram of the experimental arrangement that was used to record the LogMAR hologram is shown in Fig.1.

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Fig. 1. Schematic diagram of the experimental arrangement that was used to record the LogMAR hologram

A high contrast logMAR chart for a testing distance of 50 cm was used as the target in recording the hologram. The chart was illuminated with light from a He-Ne laser and imaged at infinity using a 2 D lens. The image forming wavefront emerging from the lens was intercepted by a holographic plate placed close beyond the lens. A path matched plane reference wave derived from the same laser was incident simultaneously at the holographic plate to record the image forming wavefront as an interference pattern in the hologram. The hologram that was exposed to the interference pattern was developed and bleached to obtain the phase hologram of the logMAR chart.

To test the vision of various subjects using this hologram, the experimental arrangement shown in Fig.2 is used. The subject places his eye close to the hologram, while the hologram is illuminated from behind by a plane reference wave travelling in the opposite direction that was used in recording the hologram. When the hologram is thus illuminated, the phase conjugated image forming wavefront emerging from the 2 D lens is recreated and the subject sees the image of the logMAR chart at infinity.

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Fig.2. Using the LogMAR hologram to test vision.

16 Myopic subjects, 16 emmetropic subjects, and 15 hyperopic subjects were included in this study. The spherical equivalent refractive error for the myopic subjects was in the range of –4.75 D to –0.5 D. Subjects with mean spherical refractive error in the range of –0.25 D to +0.25 D were considered as emmetropic subjects. The spherical equivalent refractive error for the hyperopic subjects was in the range of +0.375 D to +2.875 D. Subjects with astigmatic error greater than 0.5 D were not included in the study. Ethics approval was obtained from the Human Research Ethics Committee, UNSW. Informed consent was obtained from subject/parent according to the age of the subject. The spectacle correction for the subject was determined by subjective refraction using a phoropter. The maximum plus lens for best visual acuity was the criterion for the subjective end point. The visual acuity was 6/7.5 or greater and subjects had no significant ocular pathology. For all the subjects, the left eye was tested under mesopic condition.

Subjects were asked to view through the logMAR hologram with a +2 D lens placed over the spherical equivalent of their spectacle correction. The smallest letter size that they could recognize in the holographic logMAR chart was used to measure their vision in the presence of +2 D of blur. The measurements were then repeated with a +1 D lens to blur. The visual acuity of the subjects without any lens to blur their vision was also measured.

The subjects were then asked to look at a high contrast LogMAR chart projected at 6 metre distance through a Red filter (Kodak Filter–Wratten 25) and the same set of measurements with and without the +2 D and +1 D lenses to blur were repeated. Finally, the same set of measurements were repeated using a high contrast LogMAR chart projected at 6 metre distance in white light.

The results obtained are shown in Tables 1-3.

Table. 1 Vision (LogMAR values) with +2 D blur

Refractive Groups	White Light		Red Light		Laser Light	
	Mean	SD	Mean	SD	Mean	SD
Myope	0.87	0.14	0.90	0.07	1.04	0.04
Emmetrope	0.94	0.09	0.90	0.08	1.06	0.02
Hyperope	0.89	0.13	0.84	0.26	1.03	0.07
Overall mean:	0.89	-	0.87	-	1.04	-

Table. 2 Vision (LogMAR values) with +1 D blur

Refractive Groups	White Light		Red Light		Laser Light	
	Mean	SD	Mean	SD	Mean	SD
Myope	0.44	0.13	0.54	0.12	0.87	0.09
Emmetrope	0.44	0.14	0.49	0.11	0.88	0.08
Hyperope	0.48	0.17	0.51	0.19	0.86	0.14
Overall mean:	0.45	-	0.52	-	0.86	-

Tables 1 and 2 show that when a +2 D or a +1 D blur is introduced, there is no difference in the vision of the various refractive error groups irrespective of the illumination condition. This shows that the multivergence nature of the target in the hologram and not the illumination used was responsible for the observed differences in vision between myopic and hyperopic subjects in our earlier studies.

Table. 3 Visual Acuity (LogMAR values) with no blur

Refractive Groups	White Light		Red Light		Laser Light	
	Mean	SD	Mean	SD	Mean	SD
Myope	0.02	0.02	0.09	0.06	0.55	0.11
Emmetrope	0.01	0.02	0.08	0.05	0.53	0.10
Hyperope	0.01	0.02	0.06	0.04	0.56	0.14
Overall mean:	0.02	-	0.08	-	0.55	-

A plot of the visual acuity that was obtained under various illuminations for all the subjects is shown in Fig. 3. For all refractive groups the logMAR value of the mean VA is close to 0 under white incoherent light. For red incoherent light, the mean VA falls by 3 letters. For, red coherent light (laser illumination), the mean VA falls by 5 lines.

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Fig.3. Visual acuity of all subjects under various illuminations.

With +1 D blur under white incoherent light the mean vision is close to 0.45 logMAR. For red incoherent light the mean vision is close to 0.52, falling by 3 letters as compared to white light and for the hologram the mean vision is close to 0.86, falling by 4 lines as compared to white light for all subjects. For each illumination condition the +1 D blur has worsened the vision for all subjects uniformly by 3-4 lines in the LogMAR chart.

When a +2 D blur is given the vision tends to be similar for all subjects under white and red incoherent light, and is worst through the hologram falling by about 0.2 logMAR.

In conclusion, results obtained from this study indicate that multivergence targets in a hologram enable hyperopic subjects to tolerate more positive blur than myopic subjects. When the blur was provided artificially with a positive lens to distance corrected subjects viewing a logMAR chart at infinity in a hologram there was no difference in the blur tolerance between hyperopic and myopic subjects. Thus the holographic multivergence target is able to bring out a difference in the vision of hyperopic and myopic subjects. This could serve as a valuable tool in the early detection of myopia/hyperopia. For any imaging system the high frequency cut-off under incoherent illumination is more than under coherent illumination and the human eye is no exception! This is substantiated by the fact that the visual acuity of subjects measured using a LogMAR hologram was worse than the visual acuity that was obtained with a conventional LogMAR chart under incoherent red/white illumination. For a given illumination, there is no significant difference between the refractive groups.

This study has also indicated that to measure the refractive error using a multivergence holographic target, large size characters should be used, preferably 6/30 (20/100). Once standardized and calibrated a logMAR hologram can serve as a compact open field target to measure visual acuity.

References:

1. Kodikullam V Avudainayagam and Chitralekha S Avudainayagam, Opt. Lett. 28, 123, (2003).
2. Kodikullam V. Avudainayagam and Chitralekha S. Avudainayagam, Opt. Lett. 32, 1926, (2007).
3. Kodikullam V Avudainayagam, Chitralekha S. Avudainayagam, Nicholas Nguyen, Kian W Chiam and Cann Truong, J. Opt. Soc. Am. A 24, 3037, (2007).
4. Kodikullam V Avudainayagam, Chitralekha S Avudainayagam, and Nicholas Nguyen, "Holographic target throws more light on the vision of hyperopes", International Commission for Optics ICO – 2008 Congress, Sydney, Australia, July 2008.
5. Nicholas Nguyen, Kodikulllam V & Chitralekha S Avudainayagam, "Holographic target probes the vision of myopes and hyperopes," XII Biennial Scientific Meeting in Optometry, Auckland, New Zealand, Sept 2008.
6. Nicholas Nguyen, Chitralekha S. Avudainayagam, and Kodikullam V Avudainayagam "An experimental investigation of vision and recognition under positive blur using a holographic multivergence target", – Submitted to J. Opt. Soc. Am. A.

Appendix E - Participant Information Statement and Consent Form

Approval No (84073)

THE UNIVERSITY OF NEW SOUTH WALES

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Vision and Recognition

You are invited to participate in a study of vision. We hope to learn how the vision of long and short sighted people are different by showing you large blurry letters and asking you to identify them. You were selected as a possible participant in this study because of your vision and prescription.

If you decide to participate, we will:

- i- Determine your current optical prescription using conventional methods.
- ii- Show you a line of large blurry letters at a large distance. We will reduce the level of blurriness until you can recognise the line of letters.
- iii- Measure your pupil size.

Measurements will take approximately 5 minutes to 10 minutes in all for both the eyes.

All procedures are non-invasive. There are no risks of damage to the eye from the above procedure.

We cannot and do not guarantee or promise that you will receive any benefits from this study.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by law. If you give us your permission by signing this document, we plan to publish the results in scientific journals and at conferences. In any publication, information will be provided in such a way that you cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au). Any complaint you make will be investigated promptly and you will be informed out the outcome.

If you wish to receive feedback at the end of this study, we will email you a summary of the results.

Your decision whether or not to participate will not prejudice your future relations with the University of New South Wales and Eye Focus. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any additional questions later, Dr Kodikullam Avudainayagam (02-9385-6106) or Mr Nicholas Nguyen (97275517) will be happy to answer them.

You will be given a copy of this form to keep.

THE UNIVERSITY OF NEW SOUTH WALES

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

Vision and Recognition

You are making a decision whether or not to participate. Your signature indicates that, having read the information provided above, you have decided to participate.

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Signature of Research Participant	Signature of Witness
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(Please PRINT name)	(Please PRINT name)
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Date	Nature of Witness

REVOCATION OF CONSENT

Vision and Recognition

I hereby wish to WITHDRAW my consent to participate in the research proposal described above and understand that such withdrawal WILL NOT jeopardise any treatment or my relationship with The University of New South Wales and Eye Focus.

…………………………………………………… ……………………………………………………

Signature Date

……………………………………………………

Please PRINT Name

The section for Revocation of Consent should be forwarded to Dr Avudainayagam at the School of Optometry and Vision Science, the University of New South Wales, SYDNEY 2052 AUSTRALIA.

Approval No (07127)

THE SCHOOL OF OPTOMETRY AND VISION SCIENCE

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Measurement of the focusing error of the human eye using Holography

(LogMar Chart – study1)

You are invited to participate in a study of vision. We hope to learn how the vision of long and short sighted people are different by showing you large blurry letters and asking you to identify them. You were selected as a possible participant in this study because of your vision and prescription and because you have healthy eyes.

If you decide to participate:

i- We will determine your current optical prescription using conventional methods.
ii- With your corrected eye you will see a blurred letter chart in red light through a hologram (which is like a glass plate).
iii- We will ask you to tell us the smallest line of letters you can recognise in the chart.
iv- We will repeat the same by reducing the level of blur in the chart and without any blur in the chart.
v- We will also do the tests using a normal letter chart at a large distance in red / white light.
vi- Finally we will measure your pupil size.

Measurements will be made using one eye and will take approximately 10 minutes.

All procedures are non-invasive. There are no risks of damage to the eye from the above procedure.

We cannot and do not guarantee or promise that you will receive any benefits from this study.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by law. If you give us your permission by signing this document, we plan to publish the results in scientific journals and at conferences. In any publication, information will be provided in such a way that you cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au). Any complaint you make will be investigated promptly and you will be informed of the outcome.

If you wish to receive feedback at the end of this study, we will email you a summary of the results.

Your decision whether or not to participate will not prejudice your future relations with the University of New South Wales and Eye Focus. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any additional questions later, Dr Kodikullam Avudainayagam (02-9385-6106) or Mr Nicholas Nguyen (97275517) will be happy to answer them.

You will be given a copy of this form to keep.

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

Measurement of the focusing error of the human eye using Holography

(LogMar Chart – study1)

You are making a decision whether or not to participate. Your signature indicates that, having read the information provided above, you have decided to participate.

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Signature of Research Participant (*Optional for children under 14 years)*	Signature of Witness
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(Please PRINT name)	(Please PRINT name)
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Date	Nature of Witness

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Signature of Parent / Guardian

(*For all children under 16 years)*

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(Please PRINT name)

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Date

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

REVOCATION OF CONSENT

Measurement of the focusing error of the human eye using Holography

(LogMar Chart – study1)

I hereby wish to WITHDRAW my consent to participate in the research proposal described above and understand that such withdrawal WILL NOT jeopardise any treatment or my relationship with The University of New South Wales and Eye Focus.

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Signature of Research Participant

(*Optional for children under 14 years*) Date

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Please PRINT Name

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Signature of Parent / Guardian

(*For all children under 16 years)*

…………………………………………………… ……………………………………………………

(Please PRINT name) Date

The section for Revocation of Consent should be forwarded to (*Dr. K. V. Avudainayagam, School of Optometry and Vision Science, UNSW, NSW-2052*).

Approval No (07127)
THE SCHOOL OF OPTOMETRY AND VISION SCIENCE

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Measurement of the focusing error of the human eye using Holography
(LogMar Chart – study2)

You are invited to participate in a study of vision. We hope to learn how the vision of long and short sighted people are different by showing you large blurry letters and asking you to identify them. You were selected as a possible participant in this study because of your vision and prescription and because you have healthy eyes.

If you decide to participate:

vii- We will determine your current optical prescription using conventional methods.
viii- Without your spectacle correction you will see a letter chart in red light through a hologram (which is like a glass plate).
ix- We will ask you to tell us the smallest line of letters you can recognise in the chart.
x- We will repeat the same after giving you your spectacle correction.
xi- We will also do the tests using a normal letter chart at a large distance in red / white light.
xii- Finally we will measure your pupil size.

Measurements will be made using one eye and will take approximately 10 minutes.

All procedures are non-invasive. There are no risks of damage to the eye from the above procedure.

We cannot and do not guarantee or promise that you will receive any benefits from this study.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by law. If you give us your permission by signing this document, we plan to publish the results in scientific journals and at conferences. In any publication, information will be provided in such a way that you cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au). Any complaint you make will be investigated promptly and you will be informed of the outcome.

If you wish to receive feedback at the end of this study, we will email you a summary of the results.

Your decision whether or not to participate will not prejudice your future relations with the University of New South Wales and Eye Focus. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any additional questions later, Dr Kodikullam Avudainayagam (02-9385-6106) or Mr Nicholas Nguyen (97275517) will be happy to answer them.

You will be given a copy of this form to keep.

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

Measurement of the focusing error of the human eye using Holography

(LogMar Chart – study2)

You are making a decision whether or not to participate. Your signature indicates that, having read the information provided above, you have decided to participate.

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Signature of Research Participant (*Optional for children under 14 years)*	Signature of Witness
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Date	Nature of Witness

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Signature of Parent / Guardian

(*For all children under 16 years)*

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(Please PRINT name)

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Date

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

REVOCATION OF CONSENT

Measurement of the focusing error of the human eye using Holography
(LogMar Chart – study2)

I hereby wish to WITHDRAW my consent to participate in the research proposal described above and understand that such withdrawal WILL NOT jeopardise any treatment or my relationship with The University of New South Wales and Eye Focus.

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Signature of Research Participant
(*Optional for children under 14 years)* Date

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Please PRINT Name

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Signature of Parent / Guardian
(*For all children under 16 years)*

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(Please PRINT name) Date

The section for Revocation of Consent should be forwarded to (*Dr. K. V. Avudainayagam, School of Optometry and Vision Science, UNSW, NSW-2052*)

UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Approval No (10094)
THE SCHOOL OF OPTOMETRY AND VISION SCIENCE

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Blur and Recognition using an Optometer

You are invited to participate in a study of vision. We hope to learn how the vision of long and short sighted people are different by showing you large blurry letters and asking you to identify them. You were selected as a possible participant in this study because of your vision and prescription and because you have healthy eyes.

If you decide to participate, we will:

i - Determine your current optical prescription using conventional methods.
ii- Ask you to look into an instrument with one eye and read the letters that you can recognise first in red light and then in white light.
iii- Measure your pupil size.

The test will be carried out only on one eye and will take approximately 5 to 10 minutes in all.

All procedures are non-invasive. There are no risks of damage to the eye from the above procedure.

We cannot and do not guarantee or promise that you will receive any benefits from this study.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by law. If you give us your permission by signing this document, we plan to publish the results in scientific journals and at conferences. In any publication, information will be provided in such a way that you cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au). Any complaint you make will be investigated promptly and you will be informed of the outcome.

If you wish to receive feedback at the end of this study, we will email you a summary of the results.
Your decision whether or not to participate will not prejudice your future relations with the University of New South Wales and Eye Focus. If you decide not to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any additional questions later, Dr Kodikullam Avudainayagam (02-9385-6106) or Mr Nicholas Nguyen (97275517) will be happy to answer them.

You will be given a copy of this form to keep.

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

(Blur and Recognition using an Optometer)

You are making a decision whether or not to participate. Your signature indicates that, having read the information provided above, you have decided to participate.

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Signature of Research Participant (*Optional for children under 14 years)*	Signature of Witness
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Date	Nature of Witness

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Signature of Parent / Guardian

(*For all children under 16 years)*

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(Please PRINT name)

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Date

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

REVOCATION OF CONSENT

(Blur and Recognition using an Optometer)

I hereby wish to WITHDRAW my consent to participate in the research proposal described above and understand that such withdrawal WILL NOT jeopardise any treatment or my relationship with The University of New South Wales and Eye Focus.

………………………………………………… ………………………………………………….

Signature of Research Participant

(*Optional for children under 14 years)* Date

…………………………………………………

Please PRINT Name

…………………………………………………

Signature of Parent / Guardian

(*For all children under 16 years)*

………………………………………………… …………………………………………………

(Please PRINT name) Date

The section for Revocation of Consent should be forwarded to (*Dr. K. V. Avudainayagam, School of Optometry and Vision Science, UNSW, NSW-2052*).

Approval No (10094)
THE SCHOOL OF OPTOMETRY AND VISION SCIENCE

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Blur and Recognition using an Optometer

You are invited to participate in a study of vision. We hope to learn how the vision of long and short sighted people are different by showing you large blurry letters and asking you to identify them. You were selected as a possible participant in this study because of your vision and prescription and because you have healthy eyes.

If you decide to participate, we will:

- i- Determine your current optical prescription using conventional methods.
- ii- Ask you to look into an instrument with one eye and read the letters that you can recognise first in red light and then in white light.
- iii- Measure your pupil size.

The test will be carried out only on one eye and will take approximately 5 to 10 minutes in all.

All procedures are non-invasive. There are no risks of damage to the eye from the above procedure.

We cannot and do not guarantee or promise that you will receive any benefits from this study.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by law. If you give us your permission by signing this document, we plan to publish the results in scientific journals and at conferences. In any publication, information will be provided in such a way that you cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au). Any complaint you make will be investigated promptly and you will be informed of the outcome.

If you wish to receive feedback at the end of this study, we will email you a summary of the results.

Your decision whether or not to participate will not prejudice your future relations with the University of New South Wales and Eye Focus. If you decide not to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any additional questions later, Dr Kodikullam Avudainayagam (02-9385-6106) or Mr Nicholas Nguyen (97275517) will be happy to answer them.

You will be given a copy of this form to keep.

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

(Blur and Recognition using an Optometer)

You are making a decision whether or not to participate. Your signature indicates that, having read the information provided above, you have decided to participate.

………………………………………………… Signature of Research Participant (*Optional for children under 14 years)*	…………………………………………………. Signature of Witness
………………………………………………… (Please PRINT name)	…………………………………………………. (Please PRINT name)
………………………………………………… Date	…………………………………………………. Nature of Witness

…………………………………………………
Signature of Parent / Guardian
(*For all children under 16 years)*

…………………………………………………
(Please PRINT name)

…………………………………………………
Date

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

REVOCATION OF CONSENT

(Blur and Recognition using an Optometer)

I hereby wish to WITHDRAW my consent to participate in the research proposal described above and understand that such withdrawal WILL NOT jeopardise any treatment or my relationship with The University of New South Wales and Eye Focus.

…………………………………………………… ……………………………………………………

Signature of Research Participant

(*Optional for children under 14 years*) Date

……………………………………………………

Please PRINT Name

……………………………………………………

Signature of Parent / Guardian

(*For all children under 16 years)*

…………………………………………………… ……………………………………………………

(Please PRINT name) Date

The section for Revocation of Consent should be forwarded to (*Dr. K. V. Avudainayagam, School of Optometry and Vision Science, UNSW, NSW-2052*).

Appendix F - Photos

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intentionally removed

F1. Setup for measuring the vergence of the MVT images

The MVT hologram on the far right is reconstructed to pass through a condensing lens and the image is directed towards the diffuse screen. The screen could be slid along the optical rail until a holographic image of the target could be focussed onto the screen. The telescope is set to focus on the diffuse screen, and is used by the user to focus the holographic image. The distance when the screen is in focus from the imaging lens is an indication of the holographic object vergence. Two or more measurements were taken and the average was used to calculate the holographic object vergence.

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F2. Actual setup for recording the MVT hologram

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F3. Inside the optometer used in Chapter 7

It shows the lens, laser diodes, white LED for future experiments, the MVT on an adjustable stage.

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F4. The target for the optometer study. The MVT had an angular size of 50’ and required a height of 0.75mm at 5cm (focal length of imaging lens). This was achieved using a laser printer (Figure F4).

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F5. Optometer showing the lens aperture for subjects to view through.

There is also a provision to insert trial lenses to correct for the subject's spherical ametropia.

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F6. Setup used in clinic for hologram reconstruction

Starting from the right, the He-Ne laser used for recording is also used here for reconstruction. The beam passes through a spatial filter and is collimated by lens. The mirror on the far left is used to direct the reference beam towards the hologram at the appropriate angle.

F7. LogMAR hologram used to record the logMAR hologram

The size is appropriate for recording with a +2 D lens.

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F8. logMAR chart illuminated with laser light to simulate the holographic logMAR chart

References

Adams, D. W., & McBrien, N. A. (1992). Prevalence of myopia and myopic progression in a population of clinical microscopists. *Optom Vis Sci, 69*(6), 467-473.

Aggarwala, K. R., Nowbotsing, S., & Kruger, P. B. (1995). Accommodation to monochromatic and white-light targets. *Invest Ophthalmol Vis Sci, 36*(13), 2695-2705.

Alsbirk, P. H. (1979). Refraction in adult West Greenland Eskimos. A population study of spherical refractive errors including oculometric and familial correlations. *Acta Ophthalmol, 57*, 84-95.

Altman, J. H. (1966). Pure relief images in type 649 F plates. *Appl Opt, 5*, 1689-1690.

Alward, W. L., Bender, T. R., Demske, J. A., & Hall, D. B. (1985). High prevalence of myopia among young adult Yupik Eskimos. *Can J Ophthalmol, 20*(7), 241-245.

Anonymous. (n. d.). *Partial List of Physiological and Psychological Apparatus*. 1901 Catalogue. The Chicago Laboratory Supply and Scale Co. Chicago.

Artal, P., Schwarz, C., Canovas, C., & Mira-Agudelo, A. (2012). Night myopia studied with an adaptive optics visual analyzer. *PLoS One, 7*(7), e40239. doi: 10.1371/journal.pone.0040239

Artigas, J. M., Buades, M. J., & Felipe, A. (1994). Contrast sensitivity of the visual system in speckle imagery. *Journal of the Optical Society of America A, 11*(9), 2345-2349. doi: 10.1364/JOSAA.11.002345

Artigas, J. M., & Felipe, A. (1988). Effect of luminance on photopic visual acuity in the presence of laser speckle. *J Opt Soc Am A, 5*(10), 1767-1771.

Avudainayagam, K. V., Avudainayagam, C., & Nguyen, H. N. (2015). A Test for Progressive Myopia and the Role of Latent Accommodation in its Development. *International Journal of Ophthalmology and Clinical Research*(2).

Avudainayagam, K. V., Avudainayagam C. S., and Nguyen, N. H. N. (2008). *Holographic multivergence target throws more light on the vision of hyperopes.* Paper presented at the ICO-21 Proceedings, Sydney.

Avudainayagam, K. V., & Avudainayagam, C. S. (2003). Holographic multivergence target for subjective measurement of the spherical power error of the human eye. *Opt Lett, 28*(2), 123-125.

Avudainayagam, K. V., & Avudainayagam, C. S. (2007). Holographic multivergence target for subjective measurement of the astigmatic error of the human eye. *Opt Lett, 32*(13), 1926-1928.

Avudainayagam, K. V., Avudainayagam, C. S., Nguyen, N., Chiam, K. W., & Truong, C. (2007). Performance of the holographic multivergence target in the subjective measurement of spherical refractive error and amplitude of accommodation of the human eye. *J Opt Soc Am (A), 24*(10), 3037-3044.

Bagheri, A., Givrad, S., Yazdani, S., & Reza Mohebbi, M. (2007). Optimal dosage of cyclopentolate 1% for complete cycloplegia: a randomized clinical trial. *Eur J Ophthalmol, 17*(3), 294-300.

Bahuguna, R. D., Singh, K., & Malacara, D. (1984). White-light speckle optometer. *Journal of the Optical Society of America A, 1*(1), 132-134. doi: 10.1364/JOSAA.1.000132

Bartolini, R. A. (1977). Optical recording media review. In Optical Storage Materials & Methods. *Proceedings of the SPIE, 123*, 2-9.

Benjamin, W. J. (2006). *Borish's Clinical Refraction - E-Book*: Elsevier Health Sciences.

Bennett, A. G. (1963). The theory of bichromatic tests. *Optician, 146*, 291-296.

Bennett, A. G. (1986). An historical review of optometric principles and techniques. *Ophthalmic Physiol Opt, 6*(1), 3-21.

Benton, S. A. (1971). Granularity effects in phase holograms. *J Opt Soc Am, 61*, 649.

Berger, I. B., Spitzberg, L. A., Nnadozie, J., Bailey, N., Feaster, J., Kuether, C., . . . Swann, S. (1993). Testing the FOCOMETER--A new refractometer. *Optom Vis Sci, 70*(4), 332-338.

Bjelkhagen, H. I. (1993). *Silver-Halide Recording Materials*. New York: Springer-Verlag Berlin Heidelberg.

Bjelkhagen, H. I. (2005). Holographic Recording Materials and Their Processing. In B. D. Guenther, D. G. Steel & L. Bayvel (Eds.), *Encyclopedia of Modern Optics* (Vol. 2, pp. 47-57). Oxford: Elsevier.

Blackhurst, D. W., & Maquire, M. G. (1989). Reproducibility of refraction and visual acuity measurement under a standard protocol. The Macula Photocoagulation Study Group. *Retina, 9*(3), 163-169.

Blanche, P. (2013). Holographic Visualization of 3D Data. In G. Cristobal, P. Schelkens & H. Thienpoint (Eds.), *Optical and Digital Image Processing*: John Wiley & Sons.

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet, 1*(8476), 307-310. doi: S0140-6736(86)90837-8 [pii]

Bobier, W. R., Campbell, M. C., & Hinch, M. (1992). The influence of chromatic aberration on the static accommodative response. *Vision Res, 32*(5), 823-832.

Borish, I. M. (1970). *Clinical Refraction* (3rd ed.). Chicago: Professional Press.

Borish, I. M., & Benjamin, W. J. (2006). Chapter 20 - Monocular and Binocular Subjective Refraction *Borish's Clinical Refraction (Second Edition)* (pp. 790-898). Saint Louis: Butterworth-Heinemann.

Bourne, R. R., Stevens, G. A., White, R. A., Smith, J. L., Flaxman, S. R., Price, H., . . . Vision Loss Expert, G. (2013). Causes of vision loss worldwide, 1990-2010: a systematic analysis. *Lancet Glob Health, 1*(6), e339-349. doi: 10.1016/S2214-109X(13)70113-X

Brooks, R. E., Heflinger, L. O., & Wuerker, R. F. (1965). interferometry with a holographically reconstructed comparison beam. *Applied Physics Letters, 7*, 248-249.

Brown, E. V. L. (1938). Net Average yearly change in refraction of atropinized eyes from birth to beyond middle life. *Acta Ophthalmol, 19*, 719-734.

Brown, E. V. L. (1942). Use-abuse theory of changes in refraction versus biologic theory. *Arch Ophthalmol, 28*, 845-850.

Bullimore, M. A., Fusaro, R. E., & Adams, C. W. (1998). The repeatability of automated and clinician refraction. *Optom Vis Sci, 75*(8), 617-622.

Bullimore, M. A., & Gilmartin, B. (1987). Aspects of tonic accommodation in emmetropia and late-onset myopia. *Am J Optom Physiol Opt, 64*(7), 499-503.

Burch, J. M. (1965). The application of lasers in prodution engineering. *The Production Engineer, 44*, 431-442.

Burckhardt, C. B. (1967). Efficiency of a dielectric grating. *J Opt Soc Am, 57*, 601-603.

Casasent, D., & Caimi, F. (1977). Photodichroic crystals for coherent optical data processing. *Optics & Laser Technology, 9*, 63-68.

Cathay Jr, W. T. (1965). Three dimensional wavefront reconstruction using a phase hologram. *J Opt Soc Am, 55*, 457.

Chang, M., & George, N. (1970). Holographic dielectric grating: theory and practice. *Appl Opt, 9*, 713-719.

Clinical trial summary report. Retrieved 24 August, 2016, from https://www.opternative.com/clinical-study

Cogan, D. G. (1937). Accommodation and the autonomic nervous system. *Arch Ophthalmol, 18*(5), 739-766. doi: 10.1001/archopht.1937.00850110055004

Collier, R. J., Doherty, E. T., & Pennington, K. S. (1965). Application of moire techniques to holography. *Applied Physics Letters, 7*, 223-225.

Collom, L. M. T., & Levene, J. R. (1977). *Clinical Refraction and Visual Science*: London: Butterworth-Heinemann.

Curtin, B. (1985). *The Myopias. Basic Science and Clinical Management*. Philadelphia: Harper & Row.

Davies, P. H. (1957). A critical analysis of bichromatic tests used in clinical refraction. *Br J Physiol Opt, 14*(3), 170-182 passim.

Denisyuk, Y. N. (1962). Photographic reconstruction of the optical properties of an object in its own scattered radiation field. *Soviet Physics - Doklady, 7*, 543-545.

Denisyuk, Y. N. (1963). On the reproduction of the optical properties of an object by the wave field of its scattered radiation. *Optics & Spectroscopy, 15*, 279-284.

Denisyuk, Y. N. (1965). On the reproduction of the optical properties of an object by the wave field of its scattered radation. II. *Optics & Spectroscopy, 18*, 152-157.

Donahue, S. P. (2004). How often are spectacles prescribed to "normal" preschool children? *J AAPOS, 8*(3), 224-229. doi: 10.1016/S1091853104000965

Donders, F. C. (1864). *On the anomalies of accommodation and refraction of the eye*. London: New Sydenham Society.

du Toit, R., Soong, K., Brian, G., & Ramke, J. (2006). Quantification of refractive error: comparison of autorefractor and focometer. *Optom Vis Sci, 83*(8), 582-588. doi: 10.1097/01.opx.0000230270.39804.54

Duane, A. (1912). Normal values of the accommodation of all ages. *J. Am. Med. Assoc, 59*, 1010-1013.

Duke-Elder, S., & Abrams, D. (1970). *System of Ophthalmology: Ophthalmic Optics and Refraction* (Vol. V): London: Henry kimpton.

Duncan Jr, R. C., & Staebler, D. L. (1977). Inorganic photochromic materials. In H. M. Smith (Ed.), *Holographic recording materials* (Vol. 20, pp. 133-160). Berlin: Springer-Verlag.

Dupont, W. D., & Plummer, W. D. (2009). PS Power and Sample Size Calculations (Version 3). Retrieved from http://biostat.mc.vanderbilt.edu/PowerSampleSize

Dupont, W. D., & Plummer, W. D., Jr. (1990). Power and sample size calculations. A review and computer program. *Control Clin Trials, 11*(2), 116-128.

El-Sum, H. M. A., & Kirkpatrick, P. (1952). Microscopy by reconstructed wavefronts. *Physical Review, 85*, 763.

Epstein, D. (1982). [Accommodation as the primary cause of night myopia]. *Klin Monbl Augenheilkd, 181*(5), 400-401. doi: 10.1055/s-2008-1055257

Eyejusters. Retrieved 24th August, 2016, from https://www.eyejusters.com/

Fledelius, H. C., & Christensen, A. C. (1996). Reappraisal of the human ocular growth curve in fetal life, infancy, and early childhood. *Br J Ophthalmol, 80*, 918-921.

French, A. N., Morgan, I. G., Burlutsky, G., Mitchell, P., & Rose, K. A. (2013). Prevalence and 5- to 6-Year Incidence and Progression of Myopia and Hyperopia in Australian Schoolchildren. *Ophthalmology*. doi: 10.1016/j.ophtha.2012.12.018

French, C. N., & Jennings, L. A. M. (1974). Errors in subjective refraction - an exploratory study. *Ophthal Optn, 14*, 797-806.

Gabor, D. (1948). A new microscopic principle. *Nature, 161*, 777-778.

Gabor, D. (1949). Microscopy by reconstructed wavefronts. *Proceedings of the Royal Society A, 197*, 454-487.

Gabor, D. (1951). Microscopy by reconstructed wavefronts. II. *Proceedings of the Physical Society (Lond.) B, 64*, 449-469.

George, S., & Rosenfield, M. (2004). Blur adaptation and myopia. *Optom Vis Sci, 81*(7), 543-547.

Goldschmidt, E. (1968). [On the etiology of myopia. An epidemiological study]. *Acta Ophthalmol (Copenh)*, Suppl 98:91+.

Goldschmidt, E. (2003). The mystery of myopia. *Acta Ophthalmol Scand, 81*(5), 431-436.

Goodman, J. A. (1969). *Introduction to Fourier Optics*. New York: McGraw Hill.

Goss, D. A., & Grosvenor, T. (1996). Reliability of refraction--a literature review. *J Am Optom Assoc, 67*(10), 619-630.

Goss, D. A., & Winkler, R. L. (1983). Progression of myopia in youth: age of cessation. *Am J Optom Physiol Opt, 60*(8), 651-658.

Graube, A. (1973). Holograms recorded with red light in dye sensitized dichromated gelatin. *Optics Communication, 8*, 251-253.

Groh, G. (1968). Multiple imaging by means of point holograms. *Appl Opt, 7*, 1643-1644.

Grosvenor, T. (1971). The neglected hyperope. *Am J Optom Arch Am Acad Optom, 48*(5), 376-382.

Grosvenor, T. (1987). A review and a suggested classification system for myopia on the basis of age-related prevalence and age of onset. *Am J Optom Physiol Opt, 64*(7), 545-554.

Grosvenor, T. (1994). Refractive component changes in adult-onset myopia: Evidence from five studies. *Clin Exp Optom, 77*, 196-205.

Grosvenor, T. (2003). Why is there an epidemic of myopia? *Clin Exp Optom, 86*(5), 273-275.

Grosvenor, T., & Scott, R. (1994). Role of the axial length/corneal radius ratio in determining the refractive state of the eye. *Optom Vis Sci, 71*, 573-579.

Grosvenor, T. P. (1996). *Primary Care Optometry: Anomalies of Refraction and Binocular Vision*: Butterworth-Heinemann.

Haines, K. A., & Hildebrand, B. P. (1965). Contour generation by wavefront reconstruction. *Physics Letters, 19*, 10-11.

Hariharan, P. (1971). Reversal processing technique for phase holograms. *Optics Communication, 3*, 119-121.

Hariharan, P. (1978). Hologram interferometry without a reference beam. *Opt Lett, 2*(5), 122-123.

Hariharan, P. (1984). *Optical Holography*. New York: Press Syndicate of the University of Cambridge.

Hariharan, P., Ramanathan, C. S., & Kaushik, G. S. (1971). Simplified processing technique for photographic phase holograms. *Optics Communication, 3*, 246-247.

Hayasaki, Y., Liu, J. P., & Georges, M. (2015). Feature issue of digital holography and 3D imaging (DH): introduction. *Appl Opt, 54*(1), DH1-2. doi: 10.1364/AO.54.000DH1

Hayasaki, Y., Zhou, C., Popescu, G., & Onural, L. (2014). Feature issue of digital holography and 3D imaging (DH) introduction. *Opt Express, 22*(23), 29117-29118. doi: 10.1364/OE.22.029117

He, M., Congdon, N., MacKenzie, G., Zeng, Y., Silver, J. D., & Ellwein, L. (2011). The child self-refraction study results from urban Chinese children in Guangzhou. *Ophthalmology, 118*(6), 1162-1169. doi: 10.1016/j.ophtha.2010.10.003

Hennessy, R. T. (1975). Instrument myopia. *J Opt Soc Am, 65*(10), 1114-1120.

Hennessy, R. T., Iida, T., Shina, K., & Leibowitz, H. W. (1976). The effect of pupil size on accommodation. *Vision Res, 16*(6), 587-589.

Heron, G., & Winn, B. (1989). Binocular accommodation reaction and response times for normal observers. *Ophthalmic Physiol Opt, 9*(2), 176-183.

Hillmann, D., Franke, G., Luhrs, C., Koch, P., & Huttmann, G. (2012). Efficient holoscopy image reconstruction. *Opt Express, 20*(19), 21247-21263. doi: 10.1364/OE.20.021247

Hillmann, D., Luhrs, C., Bonin, T., Koch, P., & Huttmann, G. (2011). Holoscopy--holographic optical coherence tomography. *Opt Lett, 36*(13), 2390-2392. doi: 10.1364/OL.36.002390

Hirsch, M. J. (1950). An analysis of inhomogeneity of myopia in adults. *Am J Optom Arch Am Acad Optom, 27*(11), 562-571.

Hofstetter, H. W. (1969). Emmetropization - biological process or mathematical artifact? *Am J Optom Arch Am Acad Optom, 46*, 447-450.

Holden, B. A. (2004). The myopia epidemic: is there a role for corneal refractive therapy? *Eye Contact Lens, 30*(4), 244-246; discussion 263-244.

Howarth, P. A., & Bradley, A. (1986). The longitudinal chromatic aberration of the human eye, and its correction. *Vision Res, 26*(2), 361-366.

Howell, D. C. (2007). *Statistical methods for psychology* (6th Edition ed.). Belmont, Calif: Thomson Wadsworth.

Hug, T., & Olitsky, S. (2007). Dilation efficacy: is 1% cyclopentolate enough? *Optometry, 78*(3), 119-121. doi: 10.1016/j.optm.2006.06.018

Hyman, L., Gwiazda, J., Hussein, M., Norton, T. T., Wang, Y., Marsh-Tootle, W., & Everett, D. (2005). Relationship of age, sex, and ethnicity with myopia progression and axial elongation in the correction of myopia evaluation trial. *Arch Ophthalmol, 123*(7), 977-987. doi: 10.1001/archopht.123.7.977

Ilechie, A. A., Abokyi, S., Owusu-Ansah, A., Boadi-Kusi, S. B., Denkyira, A. K., & Abraham, C. H. (2015). Self-refraction accuracy with adjustable spectacles among children in Ghana. *Optom Vis Sci, 92*(4), 456-463. doi: 10.1097/OPX.0000000000000561

Ingelstam, E., & Ragnarsson, S. I. (1972). Eye refraction examined by aid of speckle pattern produced by coherent light. *Vision Res, 12*(3), 411-420.

Irving, E. L., Callender, M. G., & Sivak, J. G. (1995). Inducing ametropias in hatchling chicks by defocus--aperture effects and cylindrical lenses. *Vision Res, 35*(9), 1165-1174.

Ivanoff, A. (1949). Focusing wave-length for white Light. *J Opt Soc Am, 39*(8), 718-718. doi: 10.1364/JOSA.39.000718

Jennings, J. A. M. (1973). A comparison of errors in some methods of subjective refraction. *Ophthalmol Optician, 13*(8), 11-18.

Johnson, C. A. (1976). Effects of luminance and stimulus distance on accommodation and visual resolution. *J Opt Soc Am, 66*(2), 138-142.

Johnson, C. A., & Casson, E. J. (1995). Effects of luminance, contrast, and blur on visual acuity. *Optom Vis Sci, 72*(12), 864.

Junghans, B. M., & Crewther, S. G. (2005). Little evidence for an epidemic of myopia in Australian primary school children over the last 30 years. *BMC Ophthalmol, 5*, 1. doi: 10.1186/1471-2415-5-1

Keirl, A., & Christie, C. (2007). *Clinical Optics and Refraction*. Edinburgh: Elsevier Butterworth-Heinemann.

Kellner, G. A. H. (1918). U.S. Pat. No. 1,265,671.

Kilintari, M., Pallikaris, A., Tsiklis, N., & Ginis, H. S. (2010). Evaluation of image quality metrics for the prediction of subjective best focus. *Optom Vis Sci, 87*(3), 183-189. doi: 10.1097/OPX.0b013e3181cdde32

Kim, M. K., Hayasaki, Y., Picart, P., & Rosen, J. (2013). Digital holography and 3D imaging: introduction to feature issue. *Appl Opt, 52*(1), DH1. doi: 10.1364/AO.52.000DH1

Knoll, H. A. (1952). A brief history of "Nocturnal myopia" and related phenomena. *Am J Optom Arch Am Acad Optom, 29*(2), 69-81.

Knoll, H. A. (1966). Measuring ametropia with a gas laser. A preliminary report. *Am J Optom Arch Am Acad Optom, 43*(7), 415-418.

Kogelnik, H. (1965). Holographic image projection through inhomogenous media. *Bell System Technical Journal*(44), 2451-2455.

Koomen, Scolnik, R., & Tousey, R. (1951). A study of night myopia. *J. opt. Soc. Am., 41*, 80-90.

Koretz, J. F., Kaufman, P. L., Neider, M. W., & Goeckner, P. A. (1989). Accommodation and presbyopia in the human eye--aging of the anterior segment. *Vision Res, 29*(12), 1685-1692.

Kotulak, J. C., Morse, S. E., & Wiley, R. W. (1994). The effect of knowledge of object distance on accommodation during instrument viewing. *Perception, 23*(6), 671-679.

Kruger, P. B., Aggarwala, K. R., Bean, S., & Mathews, S. (1997). Accommodation to stationary and moving targets. *Optom Vis Sci, 74*(7), 505-510.

Kruger, P. B., Mathews, S., Aggarwala, K. R., & Sanchez, N. (1993). Chromatic aberration and ocular focus: Fincham revisited. *Vision Res, 33*(10), 1397-1411.

Kruger, P. B., Mathews, S., Katz, M., Aggarwala, K. R., & Nowbotsing, S. (1997). Accommodation without feedback suggests directional signals specify ocular focus. *Vision Res, 37*(18), 2511-2526.

Kruger, P. B., Nowbotsing, S., Aggarwala, K. R., & Mathews, S. (1995). Small amounts of chromatic aberration influence dynamic accommodation. *Optom Vis Sci, 72*(9), 656-666.

Kubota, T., & Ose, T. (1979). Methods of increasing the sensitivity of methylene blue sensitized dichromated gelatin. *Appl Opt, 18*, 2538-2539.

Lang, M. M. (1980). Optical systems for the refractive examination of the eye. In E. Marg (Ed.), *Computer-Assisted Eye Examination* (pp. 39-64). San Francisco: San Francisco Press.

Larsen, J. S. (1971). The sagittal growth of the ey. Pt. III. Ultrasonic measurement of the posterior segment from birth to puberty. *Acta Ophthalmol, 49*, 441-453.

Lee, Y. Y., Lo, C. T., Sheu, S. J., & Lin, J. L. (2013). What factors are associated with myopia in young adults? A survey study in Taiwan Military Conscripts. *Invest Ophthalmol Vis Sci, 54*(2), 1026-1033. doi: 10.1167/iovs.12-10480

Leibowitz, H. W., & Owens, D. A. (1975). Anomalous myopias and the intermediate dark focus of accommodation. *Science, 189*(4203), 646-648.

Leibowitz, H. W., & Owens, D. A. (1978). New evidence for the intermediate position of relaxed accommodation. *Doc Ophthalmol, 46*(1), 133-147.

Leith, E. N., & Upatnieks, J. (1962). Reconstructed wavefronts and communication theory. *J Opt Soc Am, 52*, 1123-1130.

Leith, E. N., & Upatnieks, J. (1963). Wavefront reconstruction with continuous-tone objects. *J Opt Soc Am, 53*, 1377-1381.

Leith, E. N., & Upatnieks, J. (1964). Wavefront reconstruction with diffused illumination and three-dimensional objects. *J Opt Soc Am, 54*, 1295-1301.

Leith, E. N., & Upatnieks, J. (1966). Holographic imagery through diffusing media. *Journal of the Optical Society of America A, 57*, 975-980.

Levene, J. R. (1965). Nevill Maskelyne, F.R.S. and the discovery of night myopia. *Notes Rec. R. Soc. Lond., 20*, 100-108.

Lin, L. H. (1969). Hologram formation in hardened dichromated gelatin films. *Appl Opt, 8*, 963-966.

Lohman, A. W., & Paris, D. P. (1967). Binary Fraunhofer holograms generated by computer. *Appl Opt, 6*, 1739-1748.

Lu, S. (1968). Generating multiple images for integrated circuits by Fourier-transform holograms. *Proceedings of the IEEE, 56*, 116-117.

Luckiesh, M., & Moss, F. K. (1937). The avoidance of dynamic accommodation through the use of brightness contrast threshold. *Am J . Ophthal., 20*, 469-478.

Maddock, R. J., Millodot, M., Leat, S., & Johnson, C. A. (1981). Accommodation responses and refractive error. *Invest Ophthalmol Vis Sci, 20*(3), 387-391.

Mandelbaum, J. (1960). An accommodation phenomenon. *Arch Ophthalmol, 63*, 923-926.

McBrien, N. A., & Adams, D. W. (1997). A longitudinal investigation of adult-onset and adult-progression of myopia in an occupational group. Refractive and biometric findings. *Invest Ophthalmol Vis Sci, 38*(2), 321-333.

McBrien, N. A., & Barnes, D. A. (1984). A review and evaluation of theories of refractive error development. *ophthal physiol opt, 4*, 201-213.

McBrien, N. A., & Millodot, M. (1987). The relationship between tonic accommodation and refractive error. *Invest Ophthalmol Vis Sci, 28*(6), 997-1004.

McBrien, N. A., & Millodot, M. (1988). Differences in adaptation of tonic accommodation with refractive state. *Invest Ophthalmol Vis Sci, 29*(3), 460-469.

Medina, A. (1987a). A model for emmetropization. The effect of corrective lenses. *Acta Ophthalmol (Copenh), 65*(5), 565-571.

Medina, A. (1987b). A model for emmetropization: predicting the progression of ametropia. *Ophthalmologica, 194*(2-3), 133-139.

Michaels, D. M. (1985). Subjective methods of refraction. In D. M. Michaels (Ed.), *Visual Optics and Refraction* (3rd ed., pp. 316-334). St. Louis: CV Mosby.

Miller, R. J., Wesner, M. F., Pigion, R. G., & Martin, K. D. (1984). Overaccommodation, underaccommodation, and the clinical phoropter: a study of instrument myopia and related effects. *Am J Optom Physiol Opt, 61*(5), 293-303.

Miwa, T., & Tokoro, T. (1993). Relation between the dark focus of accommodation and refractive error--a cycloplegic study. *Optom Vis Sci, 70*(4), 328-331.

Mordi, J. A., & Ciuffreda, K. J. (1998). Static aspects of accommodation: age and presbyopia. *Vision Res, 38*(11), 1643-1653.

Morgan, I. G., Ohno-Matsui, K., & Saw, S. M. (2012). Myopia. *Lancet, 379*(9827), 1739-1748. doi: 10.1016/S0140-6736(12)60272-4

Morgan, I. G., Rose, K. A., Smith, W., & Mitchell, P. (2004). Re: Evidence for an "epidemic" of myopia. *Ann Acad Med Singapore, 33*(4), 541-543; author reply 543; discussion 544.

Morgan, M. W. (1958). Changes in refraction over a period of twenty years in a non visually selected sample. *Am J Optom Arch Am Acad Optom, 35*, 281-299.

Morgan, R. W., Speakman, J. S., & Grimshaw, S. E. (1975). Inuit myopia: an environmentally induced "epidemic"? *Can Med Assoc J, 112*(5), 575-577.

Mutti, D. O., & Bullimore, M. A. (1999). Myopia: an epidemic of possibilities? *Optom Vis Sci, 76*(5), 257-258.

N. Nguyen, C. S. A., and K. V. Avudainayagam. (2009). *Holographic target probes the vision of myopes and hyperopes.* Paper presented at the Clinical Experimental Optometry, Auckland.

Nath, N. S. N. (1938). Diffraction of light by supersonic waves. *Proceedings of the Indian Academy of Sciences, 8A*, 499-503.

Nguyen, N., Avudainayagam, C. S., & Avudainayagam, K. V. (2012). An experimental investigation of the vision of hyperopes and myopes using a hologram. *Biomed Opt Express, 3*(6), 1173-1181. doi: 10.1364/BOE.3.001173

Nguyen, N., Avudainayagam, C. S., & Avudainayagam, K. V. (2013). Role of Mandelbaum-like effect in the differentiation of hyperopes and myopes using a hologram. *J Biomed Opt, 18*(8), 85001. doi: 10.1117/1.JBO.18.8.085001

Nguyen, N. H. N. (in press). Holographic Refraction and the Measurement of Spherical Ametropia. *Optom Vis Sci*.

Ong, E., Grice, K., Held, R., Thorn, F., & Gwiazda, J. (1999). Effects of spectacle intervention on the progression of myopia in children. *Optom Vis Sci, 76*(6), 363-369.

Owens, D. A. (1979). The Mandelbaum effect: evidence for an accommodative bias toward intermediate viewing distances. *J Opt Soc Am, 69*(5), 646-652.

Park, D. J., & Congdon, N. G. (2004). Evidence for an "epidemic" of myopia. *Ann Acad Med Singapore, 33*(1), 21-26.

Pennington, K. S., Harper, J. S., & Laming, F. P. (1971). New phototechnology suitable for recording phase holograms and similar information in hardened gelatine. *Applied Physics Letters, 7*, 56-57.

Perrigin, J., Perrigin, J., & Grosvenor, T. P. (1982). A comparison of clinical refractive data obtained by three examiners. *Am J Optom Physiol Opt, 59*(6), 515-519.

Perucho, B., & Mico, V. (2014). Wavefront holoscopy: application of digital in-line holography for the inspection of engraved marks in progressive addition lenses. *J Biomed Opt, 19*(1), 16017. doi: 10.1117/1.JBO.19.1.016017

Phillips, J. R. (2005). Monovision slows juvenile myopia progression unilaterally. *Br J Ophthalmol, 89*(9), 1196-1200. doi: 10.1136/bjo.2004.064212

Pickett-Seltner, R. L., Sivak, J. G., & Pasternak, J. J. (1988). Experimentally induced myopia in chicks: morphometric and biochemical analysis during the first 14 days after hatching. *Vision Res, 28*(2), 323-328.

Polasky, M. (1991). Monocular subjective refraction. In J. B. Eskridge, J. B. Amos & J. D. Bartlett (Eds.), *Clinical Procedures in Optometery* (pp. 174-188). Philadelphia: JB Lippincott.

Poon, T. C., Lee, B., Yoshikawa, H., & Osten, W. (2008). Digital holography and 3D imaging: Introduction to the feature issue. *Appl Opt, 47*(19), DH1.

Poulere, E., Moschandreas, J., Kontadakis, G. A., Pallikaris, I. G., & Plainis, S. (2013). Effect of blur and subsequent adaptation on visual acuity using letter and Landolt C charts: differences between emmetropes and myopes. *Ophthalmic Physiol Opt, 33*(2), 130-137. doi: 10.1111/opo.12020

Powell, R. L., & Stetson, K. A. (1965). Interferometric vibration analysis by wavefront reconstruction. *J Opt Soc Am, 55*, 1593-1598.

Pujol, J., Ondategui-Parra, J. C., Badiella, L., Otero, C., Vilaseca, M., & Aldaba, M. (2016). Spherical subjective refraction with a novel 3D virtual reality based system. *J Optom*. doi: 10.1016/j.optom.2015.12.005

Rabbetts, R. B. (1984). Oblique astigmatism of trial lenses. *Ophthal Optn, 24*, 864-867.

Rabbetts, R. B. (2007). *Bennett & Rabbetts' Clinical Visual Optics*: Elsevier/Butterworth Heinemann.

Radhakrishnan, H., Pardhan, S., Calver, R. I., & O'Leary, D. J. (2004). Unequal reduction in visual acuity with positive and negative defocusing lenses in myopes. *Optom Vis Sci, 81*(1), 14-17.

Ramsdale, C., & Charman, W. N. (1989). A longitudinal study of the changes in the static accommodation response. *Ophthalmic Physiol Opt, 9*(3), 255-263.

Reese, E. E., & Fry, G. A. (1941). The effect of fogging lenses on accommodation. *Am J Optom and Archiv Optom, 18*, 9-16.

Richards, O. W. (1976). Instrument myopia--microscopy. *Am J Optom Physiol Opt, 53*(10), 658-663.

Richler, A., & Bear, J. C. (1980a). The distribution of refraction in three isolated communities in Western Greenland. *Am J Optom Physiol Opt, 57*, 861-871.

Richler, A., & Bear, J. C. (1980b). Refraction, near work and education: A population study in Newfoundland. *Acta Ophthalmol 58*, 468-477.

Rogers, G. L. (1952). Experiments in diffration microscopy. *Proceedings of the Royal Society of Edinburgh, 63A*, 193-221.

Ronchi, L., & Fontana, A. (1975). Methods currently adopted for testing sight. *Ophthalmic Res, 7*(6), 447-451.

Rosenfield, M. (2006). Chapter 1 - Refractive Status of the Eye *Borish's Clinical Refraction (Second Edition)* (pp. 3-34). Saint Louis: Butterworth-Heinemann.

Rosenfield, M., & Chiu, N. N. (1995). Repeatability of subjective and objective refraction. *Optom Vis Sci, 72*(8), 577-579.

Rosenfield, M., & Ciuffreda, K. J. (1991). Effect of surround propinquity on the open-loop accommodative response. *Invest Ophthalmol Vis Sci, 32*(1), 142-147.

Rosenfield, M., Hong, S. E., & George, S. (2004). Blur adaptation in myopes. *Optom Vis Sci, 81*(9), 657-662.

Rosner, J., & Rosner, J. (1989). Relation between clinically measured tonic accommodation and refractive status in 6- to 14-year-old children. *Optom Vis Sci, 66*(7), 436-439.

Rucker, F. J., & Kruger, P. B. (2004). The role of short-wavelength sensitive cones and chromatic aberration in the response to stationary and step accommodation stimuli. *Vision Res, 44*(2), 197-208.

Rynders, M. C., Navarro, R., & Losada, M. A. (1998). Objective measurement of the off-axis longitudinal chromatic aberration in the human eye. *Vision Res, 38*(4), 513-522.

Safir, A., Hyams, L., Philpot, J., & Jagerman, L. S. (1970). Studies in refraction. I. The precision of retinoscopy. *Arch Ophthalmol, 84*(1), 49-61.

Saito, T., Imamura, T., Honda, T., & Tsujiuchi, J. (1980). Solvent vapour method in thermoplastic photoconductor media. *Journal of Optics, 11*, 285-292.

Saito, T., Imamura, T., Honda, T., & Tsujiuchi, J. (1981). Enhancement of sensitivity by stratifying a photoconductor on thermoplastic-photoconductor media. *Journal of Optics, 12*, 49-58.

Salmon, T. O., & Horner, D. G. (1996). A new subjective refraction method - the meridonal polarized vernier optometer. *J Am Optom Assoc, 67*(10), 559-605.

Saw, S. M., Tan, S. B., Fung, D., Chia, K. S., Koh, D., Tan, D. T., & Stone, R. A. (2004). IQ and the association with myopia in children. *Invest Ophthalmol Vis Sci, 45*(9), 2943-2948. doi: 10.1167/iovs.03-1296

Schaeffel, F., Glasser, A., & Howland, H. C. (1988). Accommodation, refractive error and eye growth in chickens. *Vision Res, 28*(5), 639-657.

Schober, H. A. W., Dehler, H., & Kassel, R. (1970). Accommodation during observations with optical instruments. *J. opt. Soc. Am., 60*, 103-107.

Shankoff, T. A. (1968). Phase holograms in dichromated gelatin. *Appl Opt, 7*, 2101-2105.

Sheppard, A. L., & Davies, L. N. (2010). Clinical evaluation of the Grand Seiko Auto Ref/Keratometer WAM-5500. *Ophthalmic Physiol Opt, 30*(2), 143-151. doi: 10.1111/j.1475-1313.2009.00701.x

Slataper, F. L. (1950). Age norms of refraction and vision. *Arch Ophthalmol, 43*, 466-481.

Smart, F. P. (1940). Some observations on crossed cylinders. *Arch Ophthalmol, 24*, 999-1000.

Smith, E. L., 3rd. (1998). Spectacle lenses and emmetropization: the role of optical defocus in regulating ocular development. *Optom Vis Sci, 75*(6), 388-398.

Smith, G. (2006). Refraction and visual acuity measurements: what are their measurement uncertainties? *Clin Exp Optom, 89*(2), 66-72. doi: 10.1111/j.1444-0938.2006.00022.x

Smith, G., & Atchison, D. A. (1997). *The eye and visual optical instruments*. New York: Cambridge University Press.

Smith, K., Weissberg, E., & Travison, T. G. (2010). Alternative methods of refraction: a comparison of three techniques. *Optom Vis Sci, 87*(3), E176-182. doi: 10.1097/OPX.0b013e3181cf86d6

Song, Y. Y., Wang, H., Wang, B. S., Qi, H., Rong, Z. X., & Chen, H. Z. (2011). Atropine in ameliorating the progression of myopia in children with mild to moderate myopia: a meta-analysis of controlled clinical trials. *J Ocul Pharmacol Ther, 27*(4), 361-368. doi: 10.1089/jop.2011.0017

Southall, J. P. C. (1918). *Prisms and Lenses*: New York: Macmillan.

Stark, L. R., & Atchison, D. A. (1998). Effect of an intervening screen on accommodation to a distant object. *Clin Exp Optom, 81*(3), 119-130.

Stein, H. A., Slatt, B. J., & Stein, R. M. (1992). *Ophthalmic Terminology: Speller and Vocabulary Builder*: Mosby.

Stroke, G. W., Restrick, R., Funkhouser, A., & Brumm, D. (1965). Resolution-retrieving compensation of source effects by correlation reconstruction in high resolution holography. *Physics Letters, 18*, 274-275.

Switkes, E., Bradley, A., & Schor, C. (1990). Readily visible changes in color contrast are insufficient to stimulate accommodation. *Vision Res, 30*(9), 1367-1376. doi: 0042-6989(90)90010-I [pii]

Teel, D. F., Copland, R. J., Jacobs, R. J., Wells, T., Neal, D. R., & Thibos, L. N. (2008). Design and validation of an infrared Badal optometer for laser speckle. *Optom Vis Sci, 85*(9), 834-842. doi: 10.1097/OPX.0b013e3181852742

Teel, D. F., Jacobs, R. J., Copland, J., Neal, D. R., & Thibos, L. N. (2014). Differences between wavefront and subjective refraction for infrared light. *Optom Vis Sci, 91*(10), 1158-1166. doi: 10.1097/OPX.0000000000000370

Thompson, B. J., Ward, J. H., & Zinky, W. R. (1967). Application of hologram techniques for particle size analysis. *Appl Opt, 6*, 519-526.

Ting, P. W., Schmid, K. L., Lam, C. S., & Edwards, M. H. (2006). Objective real-time measurement of instrument myopia in microscopists under different viewing conditions. *Vision Res, 46*(15), 2354-2362. doi: 10.1016/j.visres.2006.01.014

Tokoro, T., & Kabe, S. (1965). [Treatment of the myopia and the changes in optical components. Report II. Full-or under-correction of myopia by glasses]. *Nihon Ganka Gakkai Zasshi, 69*(2), 140-144.

Tucker, J., & Charman, W. N. (1979). Reaction and response times for accommodation. *Am J Optom Physiol Opt, 56*(8), 490-503.

Upatnieks, J., & Leonard, C. (1970). Efficiency and image contrast of dielectric holograms. *J Opt Soc Am, 60*(297-305).

Upatnieks, J., Vander Lugt, A., & Leith, E. (1966). Correction of lens aberrations by means of holograms. *Appl Opt, 5*, 589-593.

Urbach, J. C. (1977). Thermoplastic hologram recording. In H. M. Smith (Ed.), *Hologram Recording Materials* (Vol. 20, pp. 161-207). Berlin: Springer-Verlag.

Van Alphen, G. W. H. M. (1961). On emmetropia and ametropia. *Ophthalmologic (Suppl), 142*, 1-92.

Vander Lugt, A., Rotz, F. B., & Klooster Jr, A. (1965). Character reading by optical spatial filtering. In J. T. Tippett, D. A. Berkowitz, L. C. Clapp, C. J. Koester & A. Vanderburgh Jr (Eds.), *Optical & Electro-Optical Information Processing* (pp. 125-141). Cambridge: Massachusetts Institute of Technology Press.

Vasudevan, B., Ciuffreda, K. J., & Gilmartin, B. (2009). Sympathetic inhibition of accommodation after sustained nearwork in subjects with myopia and emmetropia. *Invest Ophthalmol Vis Sci, 50*(1), 114-120. doi: 10.1167/iovs.08-1762

Wald, G., & Griffin, D. R. (1947). The change in refractive power of the human eye in dim and bright light. *J Opt Soc Am, 37*(5), 321-336.

Wallman, J., & Winawer, J. (2004). Homeostasis of eye growth and the question of myopia. *Neuron, 43*(4), 447-468. doi: 10.1016/j.neuron.2004.08.008

Wang, B., Ciuffreda, K. J., & Vasudevan, B. (2006). Effect of blur adaptation on blur sensitivity in myopes. *Vision Res, 46*(21), 3634-3641. doi: 10.1016/j.visres.2006.03.015

Ward, P. A., & Charman, W. N. (1987). An objective assessment of the effect of fogging on accommodation. *Am J Optom Physiol Opt, 64*(10), 762-767.

Westheimer, G. (1957). Accommodation measurements in empty visual fields. *J Opt Soc Am, 47*(8), 714-718.

Whiteside, T. C. (1952). Accommodation of the human eye in a bright and empty visual field. *J Physiol, 118*(4), 65P-66P.

Whiteside, T. C. (1957). *The Problems of Vision in Flight at High Altitudes*: London: Butterworths.

Win-Hall, D. M., Houser, J., & Glasser, A. (2010). Static and dynamic accommodation measured using the WAM-5500 Autorefractor. *Optom Vis Sci, 87*(11), 873-882. doi: 10.1097/OPX.0b013e3181f6f98f

Wu, M. M., & Edwards, M. H. (1999). The effect of having myopic parents: an analysis of myopia in three generations. *Optom Vis Sci, 76*(6), 387-392.

Young, F. A., Leary, G. A., Baldwin, W. R., West, D. C., Box, R. A., Harris, E., & Johnson, C. (1969). The transmission of refractive errors within Eskimo families. *Optometry and Vision Science, 46*(9), 676-685.

Zhou, Z., Chen, T., Jin, L., Zheng, D., Chen, S., He, M., . . . Congdon, N. G. (2016). Self-refraction, ready-made glasses and quality of life among rural myopic Chinese children: a non-inferiority randomized trial. *Acta Ophthalmol*. doi: 10.1111/aos.13149

Zylbermann, R., Landau, D., & Berson, D. (1993). The influence of study habits on myopia in Jewish teenagers. *J Pediatr Ophthalmol Strabismus, 30*(5), 319-322.