Investigation of a new clinical method of measuring amplitude of accommodation

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Abstract

Amplitude of Accommodation (AoA) is the extent of the eye's ability to accommodate, or focus over a range of distances. This thesis describes the mechanism of accommodation and reviews the literature concerning the measurement of accommodation's amplitude, its maximum range. The reasons for measuring the amplitude of accommodation, in routine clinical practice, are outlined. The aim of this study is to investigate the accuracy of a new clinical method of measuring amplitude of accommodation and to compare it to the prevalent method.

Methods by which the amplitude of accommodation has been measured clinically are described and compared. Each method has inherent sources of error and these are examined individually to show how they affect the results of measurement. The new method of measurement, developed by the author, is introduced. Its basis, which may lead to a redefinition of amplitude of accommodation, is explained and contrasted with the rationale of existing methods. Experimental work is reported comparing accuracy of measurement using the new method (the TRU) with that of the prevalent method (Push-Up with the RAF Rule). Two techniques for using the TRU, distance-measurement and acuity-measurement, were examined and distance-measurement was shown to be more precise.

The method-comparison was by repeated measures of results with both methods and with those of an objective reference method, the WAM-5500 autorefractor. The estimated 95% limits of agreement between the two test methods spanned 6.36 D (dioptres). The disparity of results appeared due more to differences between the test methods' trueness than their precision. The RAF Rule gave results that averaged 2.10 D higher than results with the TRU and 2.19 D higher than results with the WAM-5500 autorefractor. Measurements of AoA with the autorefractor were 67% more repeatable than measurements with the TRU and 114% more repeatable than measurements with the RAF Rule, although of questionable trueness.

The estimated 95% limits of agreement of reproducibility between sessions spanned 6.57D for the established method but 2.89 D for the new method, and reproducibility between investigators similarly spanned 5.10 D for the established method and 2.56 D for the new method.

The significance of these findings for clinical vision science is discussed and examined in the light of theoretical considerations of each method's validity. Suggestions are made for improving the accuracy of measurement of the amplitude of accommodation, which should improve the reliability of normative values in current clinical use.

Acknowledgements

I would like to acknowledge the help of the following people in finishing this thesis:

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Dedication

Florence Trude Goldbrom had short curly hair and was not quite two years old. She was named Trude after my late mother-in-law and was the youngest at our family gathering. Sitting on the sofa next to her big sister Esme (5) she played busily in joy and wonder with whatever was near. Suddenly a long trailing hair drifted out of Esme's chaotic coiffure.

The hair brushed Flo's nose as it floated by, and focused her curiosity. She grasped the hair and her big brown eyes converged on it in scrutiny because, of course, she needed to know all about it. Flo froze in intelligent inquiry, holding the hair barely four inches from her face. After several seconds something across the room took her attention and she let the hair go.

I sat nearby and watched, enthralled. For years I had been researching close-up visual focussing, the subject of this thesis. The sight of Flo inspecting the hair should illustrate these forty thousand words. Everybody wants to focus like Flo, but do we?

I do not dedicate this thesis to Flo, who was only doing what people naturally do, but to my wife Ofra, Trude's daughter, who introduced me to Flo. Ofra refused to be the first reported casualty of Amplitude of Accommodation. She put up with the downside of this work and still supported my stumbling through to finish it. What's more, to my joy and wonder, Ofra remains with me.

David Burns

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Chapter 1 Background

The purpose of this thesis is to consider accuracy in the routine clinical measurement of the eye's ability, when it is optically corrected for distance vision, to adjust its focus to image finer detail in an object brought nearer to the eye.

1.1 An overview of the focussing of light

For a person to see a physical object, light from the object is focussed within the eye. Light can be focussed by two separate physical processes; refraction, and reflection. Human vision involves refraction, the deviation of the path of a ray of light that occurs when the ray passes obliquely across an interface with another transparent medium in which light travels at a different speed. The interface is known as the refracting surface.

The physical characteristics of refracting surfaces determine how they refract light. These characteristics configure the refraction, by the surface, of rays of light emitted by a point source. The shape of the surface is its principal characteristic. If the refracting surface is spherical (i.e. part of the surface of a sphere) it refracts the light so that the rays converge to, or appear to diverge from, a point focus. If it is cylindrical, the focus is not a point but a line perpendicular to the central ray. If it is prismatic (i.e. flat, but not perpendicular to the ray) rays from the source to the refracting surface are not focussed by the surface but simply deviated equally.

A lens is a discrete item that refracts light. It is a transparent medium within another transparent medium in which light travels at a different speed, bound by a pair of refracting surfaces close to each other. Glass and air are examples of transparent media, and as the speed of light in glass is quite different to its speed in air, glass is a good refracting material. The speed of light in air, divided by the speed of light in the refracting medium, is the "refractive index" of the medium.

Refracting surfaces that do not have the complete symmetry of a sphere are said to be aspheric if rotationally symmetrical: otherwise, astigmatic if they cannot form a point image (at any position, real or virtual) of a point object. Astigmatic power, prismatic power and spherical power can all be combined. Lenses or refracting surfaces can have refractive power that is positive (converging) or negative (diverging) and are often "spherical" i.e. have a refracting surface or surfaces shaped to form part of a sphere. Refractive power is measured in units known as dioptres (D) such that a one-dioptre positive spherical lens (+1 DS) in air would cause light that arises from a substantively distant point source to converge to focus at a point one metre beyond the lens (if in air or a vacuum) and a -3 DS lens would cause light from the same source to diverge from a virtual focus one-third of a metre (if in air) before that surface.

1.2 The Eye as an Optical Instrument

The eye is an organ that functions to provide information for an organism about its environment and external events. It does this through converting incident electromagnetic radiation into other forms of energy that the organism can analyse to determine whether and how to respond. Incident radiation that stimulates the eye is of certain wavelengths. These occupy a narrow band in the electromagnetic spectrum, within the range between heating and ionising radiation.

The eye is found in many forms throughout nature. That of *Homo sapiens* is similar in structure and function to those of all other mammals and of some reptiles. It is a simple optical instrument, stimulated by radiation of wavelength from about 400 to about 800 nanometres (nm) which it focuses as the refracting camera does. This principle is shown in Figure 1.1.

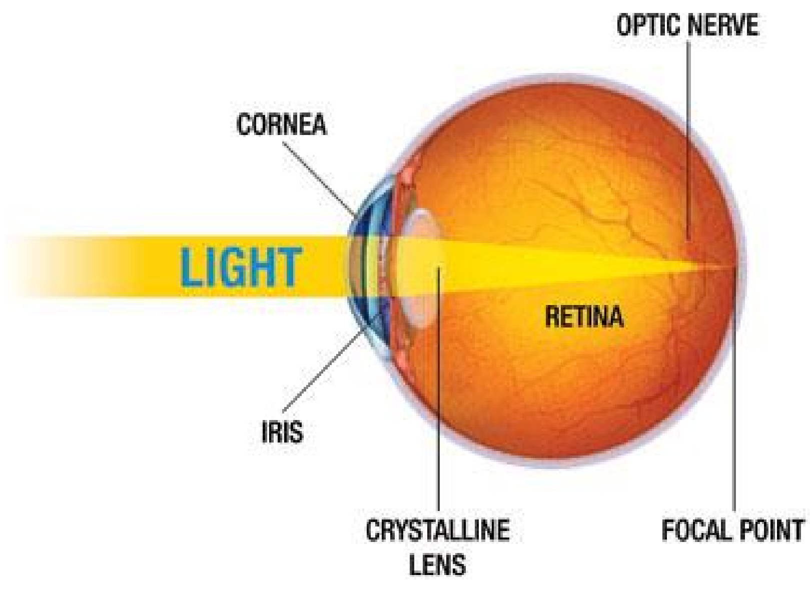

Figure 1.1 The eye as an optical instrument focusing light, from a distant point, on the retina

with acknowledgement to the National Keratoconus Foundation of the USA

1.2.1 How the human eye makes an image of external objects

As an optical instrument, the human eye has essentially four refracting surfaces. Most of the refraction occurs at the outer of these four, the front surface of the outer curved window or cornea. Here, as shown in Figure 1.1, light from an object of regard meets the eye before it passes through three more principal refracting surfaces - the back surface of the cornea and then the front and back surfaces of the eye's lens (known as "crystalline" because it contains crystallin, a protein contributing to lens transparency).

Then the light travels on to the retina to be sensed by absorbtion in cells known as photoreceptors. The photoreceptors contain pigments known as photopigments (because they are photovoltaic) and are arranged as a single layer. Their concentration is greatest in the fovea, a tiny central area of the retina where the concentration of photoreceptors allows for the most detailed sight. The shortest distance of the path of light to the fovea is known as the eye's axial length, it being the length of the schematic eye's axis of symmetry.

There are two types of photoreceptors, known as rods and cones. Rods are distributed peripherally beyond the fovea and do not cue the accommodative response (Johnson, 1976).

The retina is an outgrowth of the brain so, when it converts light energy into an electric signal, the signal can be transmitted by neurons in the brain for processing and analysis leading to the initiation of the organism's possible response to the visual stimulus. When the light arrives at the retina its focussing serves to concentrate light energy incident from each direction within the field of view to a corresponding locus on the retina. Optimal focusing causes each viewed object point to illuminate a corresponding image point on the retina, forming a composite image of the scene. This composite retinal image can be rich in spatially ordered information from which the brain builds a representation of the view to help the organism to survive, to learn and ultimately to flourish.

If the focussing is optimal, so that light from adjacent object points in the field of view is refracted to form adjacent image points on the retina, the eye can register the highest level of detail and so provides the highest concentration of data. The human eye, at its best performance, commonly resolves detail subtending less than one minute of arc at the cornea (Roberts, 1964, Elliott *et al*. 1995 using notation established by Bailey and Lovie, 1976). To permit such detailed sight, the degree of refraction must be most precise so that light from a distant object focuses exactly on the foveal photoreceptors.

1.2.1.1 How the human eye makes an image of external objects at a range of distances

If light is not from a substantively distant object it will consist of rays diverging from that object. So, to converge this light to focus on the retina, the eye's optical power must increase. Therefore, if an eye can see distant fine detail, to remain in focus when viewing a near object it can alter the physical characteristics of one or more of its refracting surfaces. This mechanical adjustment in the dioptric power of the eye to focus the retinal image of objects at a range of distances is known as accommodation. Accommodation is automatic, as is the autofocus mechanism found in some cameras. It is present in all mammalian eyes and in those of some other biological classes.

Heath (1956) introduced the concept that accommodation is driven by signals that arise from three different origins; retinal, oculomotor convergence, and psychological. Retinal accommodation is driven by the state of focus of the retinal image, convergence accommodation is the accommodation linked to the degree of the convergence of the two eyes' lines of sight as required to view the object, and psychological accommodation is driven by the observer's sense of the visual object's proximity.

To these three components of accommodation, discussed below in more detail, Keirl (2007) added a fourth, tonic accommodation, representing the resting state of accommodation. Tonic accommodation is present in the absence of a stimulus (Johnson, 1976). However, accommodation is initiated by neural signals that are principally derived from the retinal image of the object of regard. These signals are processed in the brain, to stimulate the mechanical adjustment of the eye's focus described above, refining the adjustment to maintain the best focus of the retinal image through continuous feedback.

Retinal signals arise when light from a detailed visual object stimulates the foveal photoreceptors. Certain distinct naturally-occurring ocular aberrations (imperfections of best focus) are involved in driving accommodation, as neural processing of the retinal image's configuration provides information relating to the light's vergence at the retina. The configuration of defocus, as a stimulus to accommodation, was demonstrated initially for chromatic aberration by Fincham (1951) and reviewed for non-chromatic aberrations by Lopez-Gil *et al.* (2007).

Accommodation continually fluctuates a little. These "microfluctuations of accommodation" (MA) were discovered by Collins (1937). Charman and Heron (2015) reviewed research addressing whether MA might assist in visual focussing through control of accommodation. Charman and Heron concluded that the lower-frequency MA (around 0.5 Hz, which tend to be larger and to differ in other characteristics from the higher-frequency MA which are around 1.8Hz) help to maintain a steady level of accommodation when required, in some but not all people who accommodate, but that the evidence for MA influencing the overall level of accommodation was weak. Further work by Metaplally *et al.* (2016) also failed to show direction of accommodation by MA. The lack of influence would be expected particularly at the highest levels of accommodation at which the lens' power is limited by the physical characteristics of the mechanism of accommodation as described below.

Convergence signals for accommodation arise from binocular information, as disparity between the two retinal images drives convergence which in turn influences accommodation (Marg and Morgan, 1949). Fincham and Walton (1957) examined the relationship between convergence and accommodation. They found that each function stimulated the other approximately proportionately until, with increasing age after 24 years, convergence stimulated less accommodation. They also showed that the strength of the relationship between convergence and accommodation varies considerably between individuals, and described convergence-induced accommodation as an unconditioned reflex augmenting the accommodation induced by defocus as described above.

Psychological stimulation of accommodation arises from awareness of the test object's nearness (Rosenfield and Gilmartin, 1990). Rosenfield *et al.* (1991) found that such "proximal accommodation" accounted for about 60% of the accommodative response, though Hung *et al.* (1996) found that it was less effective in more natural viewing conditions. Horwood and Riddell (2008) found that target nearness stimulated accommodation only minimally (or not at all) when other cues such as blur and interocular disparity were operating, though acknowledging substantial variation, between individuals and also between viewing conditions, in the relative effectiveness of cues to accommodation. However, Momeni-Moghaddam *et al.* (2013) measured higher levels of accommodation when research participants were aware that the object of regard was nearer.

These signals mediate adjustment of refracting power in the mammalian eye through mechanical control of the crystalline lens. The control is effected via autonomic innervation of the ciliary muscle, a ring of smooth muscle within which the lens is suspended by taut ligaments known as zonules, its diameter exceeding that of the pupil as shown in Figure 1.1. The zonules are far less elastic than the lens capsule (or the ciliary muscle) and this does not change between the ages of 8 and 45 years (Fisher, 1986).

Compared to other smooth muscle, ciliary muscle contracts faster because of its multi-unit form and the myelination of many of the motor nerves to it (Atchison, 1995). It is attached to the inner surface of the eyeball just behind the iris, approximately coaxial and parallel to it. Its location, structure and function were described by early ocular-anatomists such as Bowman (1849).

Motor innervation of the ciliary muscle was reviewed by Gilmartin (1986) who concluded that focussing was mediated by parasympathetic stimulation with sympathetic input being inhibitory, relatively weak, relatively slow to have effect, and somewhat dependent on concurrent parasympathetic input. The sympathetic muscle-innervation appeared to maintain flexibility of the accommodative response by complementing the parasympathetic input.

Any lens' optical power depends on the curvature of its refracting surfaces. The crystalline lens is deformable by ciliary muscle action as that adjusts the curvature of the lens, and hence the eye's refractive power, to maintain the best focus of light on the retina. The lens loses this deformability with age, usually soon after age 50 as discussed by Atchison (1995). Glasser and Campbell (1999) showed that throughout and beyond its accommodating life the lens, excluding its thin elastic outer layer or "capsule", steadily grows, loses elasticity, becomes more viscous, and becomes steeper (mainly anteriorly, and excluding any moulding effect of the capsule as described below). They stated that the lens' refractive index changes very little with age. However, using different methods, other authors including Richdale (2016) found that it decreased slightly.

The ciliary muscle is attached most firmly to the eye anteriorly, so when it contracts its bulk moves forward. The movement forward reduces its diameter, while the contraction of its fibres parallel to the iris also reduces its inner diameter. These changes in ciliary muscle shape on accommodation were measured by Sheppard and Davies (2010a).

The shape-changes reduce the tension of the zonules. The zonular slackening allows the lens capsule to mould the lens to be more curved at its principal refracting surfaces rather than nearer to the ciliary muscle. Therefore ciliary muscle contraction increases the eye's power (and relaxation reduces it) as first proposed by Helmholtz (1855) while the lens capsule's influence on accommodation was described and explained initially by Fincham (1937). Other mechanisms of accommodation have been postulated but

Helmholtz's theory, though it was the first scientific opinion published, has remained the most widely accepted mechanism for accommodation (Pierscionek, 1993: Charman, 2008: Glasser, 2008) and appears to be the best supported, such as by mathematical modelling (Burd *et al.,* 1999: Reilly, 2014), *in vitro* measurement (Fisher, 1986) and by observation *in vivo* (Brown, 1973: Richdale *et al.*, 2016).

Accommodation is the dominant member (Marg and Morgan, 1949) of the "near triad", three adjustments that occur together in the eye when it views objects at a different distance. The other two are convergence (the increase of the angle between the line of sight of one eye and that of its fellow, so that both eyes view the same point) and near-miosis (the reduction of pupil diameter with reduction of viewing distance).

The three ocular adjustments in the near triad are linked (Hung *et al.,* 1984). This synkinesis is not rigid. For example, if one eye of a young adult is covered and the other eye views an object that is close enough, the covered eye still turns in (though probably less than if it were uncovered to view the object) and its pupil gets smaller.

The next Section introduces the quantification of accommodation.

1.2.1.2 The Amplitude of Accommodation

The amplitude of accommodation (AoA) can be defined as the maximum increase in optical power that an eye can achieve. It is measured in dioptres.

Mechanical factors limiting it, discussed by Atchison (1995) include the amplitude of ciliary muscle movement, the deformability of the lens, the amount of energy that the lens' capsule can store, and the angles of insertion of the zonular fibres.

Accommodation is strongly influenced by age. That is a problem for everyone at or before the age of about fifty years as AoA is lost gradually, falling to zero well before the normal retirement age. This decrease has been demonstrated by population surveys. The first such survey was by Donders (1864).

Measurement of AoA is the parameter of accommodation that is most commonly assessed clinically, though accommodation can also be investigated clinically by assessing its "facility" (speed and flexibility) and its "lag" which is an aspect of its trueness. However, competency in the measurement of AoA, and in no other aspect of accommodation, is statutorily required of any aspiring optometrist (General Optical

Council, 2011). Furthermore, measurement of AoA is a recommended component of routine eye examination when “clinically appropriate” (College of Optometrists, 2017).

1.2.2 Refractive errors

If, with the ciliary muscle at rest, an eye focuses infinitely distant detail on the retina, it is termed emmetropic. Most eyes are not emmetropic if only because emmetropia requires perfect matching of many ocular physical parameters. For example, a deviation of a tenth of a millimetre in the eye’s axial length, or of one percent in the radius of curvature of the cornea, would produce a change in focus (approximately 0.33 D) that most people would notice. The non-emmetropic eye is said to have “refractive error”.

Refractive error is quantified in dioptres. It relates to the eye’s focus for distance vision without exerting accommodation, unless stated otherwise.

The principle function of the optometrist is the measurement of refractive error, to determine lenses that reduce its effect on an individual eye’s sight as much as possible. This function is a clinical measurement also termed “refraction”.

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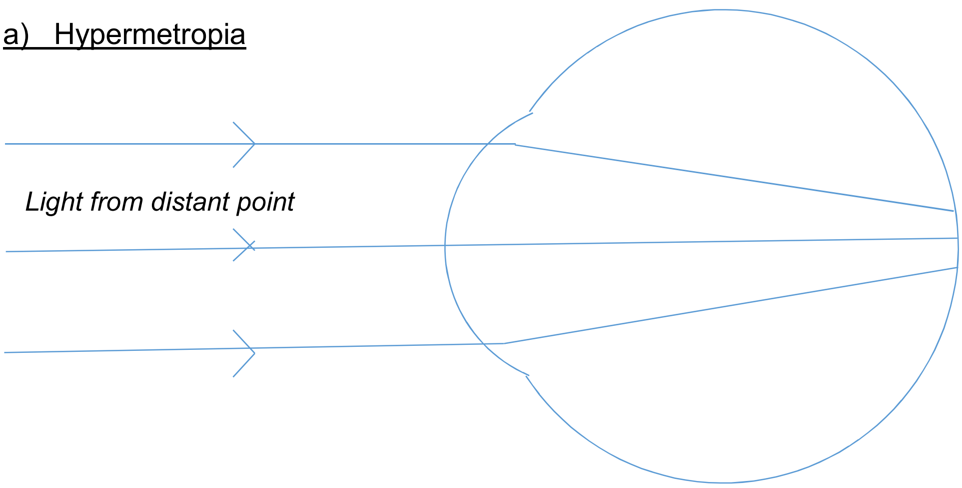
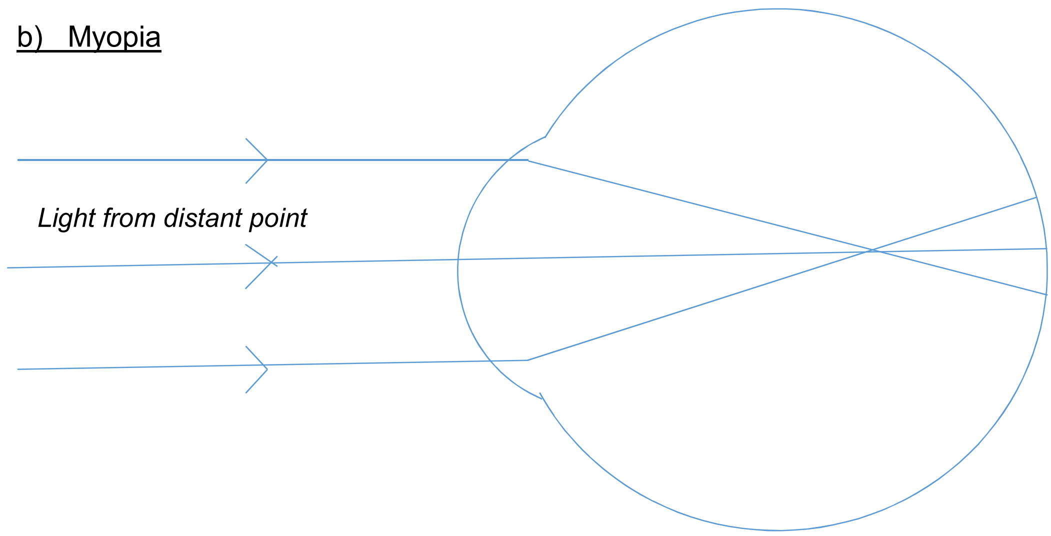
The types of refractive error that are routinely corrected by lenses prescribed by optometrists are as follows.

Figure 1.2 Refractive error, and ocular axial length and refracting power

a) Hypermetropia



b) Myopia



1.2.2.1 Hypermetropia

The distance from the front of the cornea, along the shortest line joining the refracting surfaces' centres of curvature, to the retinal photopigment layer is termed the axial length of the eye. In hypermetropia there is inadequate axial length and/or refractive power. The unaccommodated eye would therefore focus light from distant detail virtually beyond the retina, so when light arrives at the photopigments it forms an image that is not in focus. This is shown schematically in Figure 1.2a. Problems that hypermetropia may cause are eased when wearing the correct spectacles of positive dioptric power.

If accommodation can be effected it may serve to focus sight of distant detail in the hypermetropic eye. However, this use of part of the available AoA reduces the remaining dioptric amount of accommodation available for focussing close-up.

1.2.2.2 Myopia

In this condition, with excessive refractive power and/or axial length, the eye focuses light from distant detail in front of the retina so that when it reaches the retina it forms a blurred image. This is shown schematically in Figure 1.2b. Problems that myopia may cause are eased when wearing the correct spectacles of negative dioptric power.

1.2.2.3 Astigmatism

This condition is the commonest refractive error routinely corrected by spectacle lenses and is often found in a hypermetropic or a myopic eye. It is due to net rotational asymmetry in the eye's refracting surfaces. This renders the eye incapable of forming a point image of a point object. The commonest type of astigmatism, in which there is symmetry along an axis intersected by the line of sight and along a second axis perpendicular to the first, is known as regular astigmatism.

1.2.2.4 Presbyopia

Presbyopia is the last stage of the gradual loss of AoA mentioned in Section 1.2.1.2. It is a refractive error that, when all other refractive errors of an eye are corrected, can be said to be present when the angle subtended at the eye by the smallest discernible detail is greater for hand-held detail than for more distant detail. It arises when the AoA becomes inadequate as described above, introducing difficulty with common near-vision tasks such as deskwork, smartphone use, and fine manipulation.

Presbyopia affects all people over the age of "about forty" (Charman, 2008) or fifty (Tabernero et al, 2016). There is no consensus regarding precise age of onset but the commonplace incidence of presbyopia has been recognised for centuries.

The mechanism of the development of presbyopia is still not well understood, as discussed by He *et al.* (2011) and Davies *et al.* (2016). The oldest scientific theory for age-related loss of accommodation, that it arises from sclerosis of the crystalline lens with age (Helmholtz, 1855) still holds sway (Atchison, 2008; Charman, 2008; Davies *et al.*, 2016). Atchison (1995) reviewed several competing theories of the mechanism of loss of AoA with age and found that the published evidence mainly supported Helmholtz' theory.

A role for changes with age in the ciliary muscle producing the age-related decrease of AoA was proposed by Donders (1864) and that would appear the most plausible of the competing or complementary theories reviewed by Atchison (1995). However, Helmholtz' theory has sufficient empirical support to stand alone. For example, the power of the ciliary muscle to contract has been found to increase with decreasing AoA (Fisher, 1977) its range of movement has been found to not decrease while AoA does (Richdale *et al.*, 2013) and its ability to contract is not lost in old age (He *et al.*, 2011, and Tabernero *et al.*, 2016) . Glasser and Campbell (2008) showed how physical changes with age in the lens, alone, could account for the development of presbyopia. Fisher (1977) measured mounted parts of fresh cadaver eyes and correlated the age-dependent loss of accommodation with changes measured in physical parameters of the crystalline lens, concluding that its gradual stiffening rendered it less able to respond to stimuli to accommodate.

Helmholtz's theory was supported by Duane (1922) in that he felt that the ciliary muscle always contracted maximally at maximal accommodation. It was elaborated by Fincham (1937) particularly with respect to changes with age in elastic forces between the lens capsule and its contents. Perhaps that is why Helmholtz's theory, as developed by those two authors, has been termed the Duane-Fincham theory by authors including Pierscionek (1993) Atchison (1995) Radhakrishnan and Charman (2007) and Charman (2008). However, there was little other common ground between Duane and Fincham on the cause of loss of AoA with age. For example, Duane agreed with Donders (1864) that the ciliary muscle weakened with age but Fincham believed that it did not.

The Duane-Fincham theory contrasts with the Hess-Gullstrand theory, a mechanism proposed by Hess in 1901 and elaborated by Gullstrand in 1908. This proposal, summarised by Alpern (1962) was that ciliary muscle contraction remained proportional to accommodation until presbyopia was complete, so that there was an excess of contraction possible when full accommodation was exerted (except perhaps at the age of peak AoA). Atchison (1995) found that the empirical evidence for the Hess-Gullstrand theory was very weak compared to that for the Duane-Fincham theory. However Charman (2008) felt that elements of the Hess-Gullstrand theory, and age-related changes in the geometry of the zonule as described by Pierscionek and Weale (1995) may have a minor role in the aetiology of presbyopia.

One can speculate on possible societal causes of presbyopia. The decrease of AoA with age may have arisen with hunter-gatherer tribal lifestyle. Before history began to be recorded, children would have had the greatest need to see clearly near and far. They needed sharp near-vision to learn about domestic matters of survival such as preparing food and tools, grooming, and observing wounds. Adults had learnt those survival skills, and had longer arms than their children, so they did not require the higher AoA that the children needed. It could also be argued that adults had more responsibility for tribal management matters which included seeing the relatively distant detail involved in hunting, identifying friends, foes, safe goals and danger, and assessing the environment. A high amplitude of accommodation might even be a small danger for a mature hunter if using high levels of accommodation were to slightly delay sharp distance vision.

It is only a few generations, in the broad historical perspective of human development, since lifestyle changed significantly in the context of vision. Until the Industrial Revolution the gradual inability to see fine detail with increasing age was not of great consequence for most people. Then, principally during the nineteenth century, three major lifestyle changes caused the loss of AoA to become a serious problem. Most people moved to live and work predominantly indoors, where there was generally far poorer lighting than traditional outdoor occupations for which evolution had adapted the visual system. Then, typical life expectancy increased, as shown in Figure 1.3, well beyond the age of presbyopic onset. Finally, literacy and other skills requiring fine near vision became widespread, and were in turn required for survival.

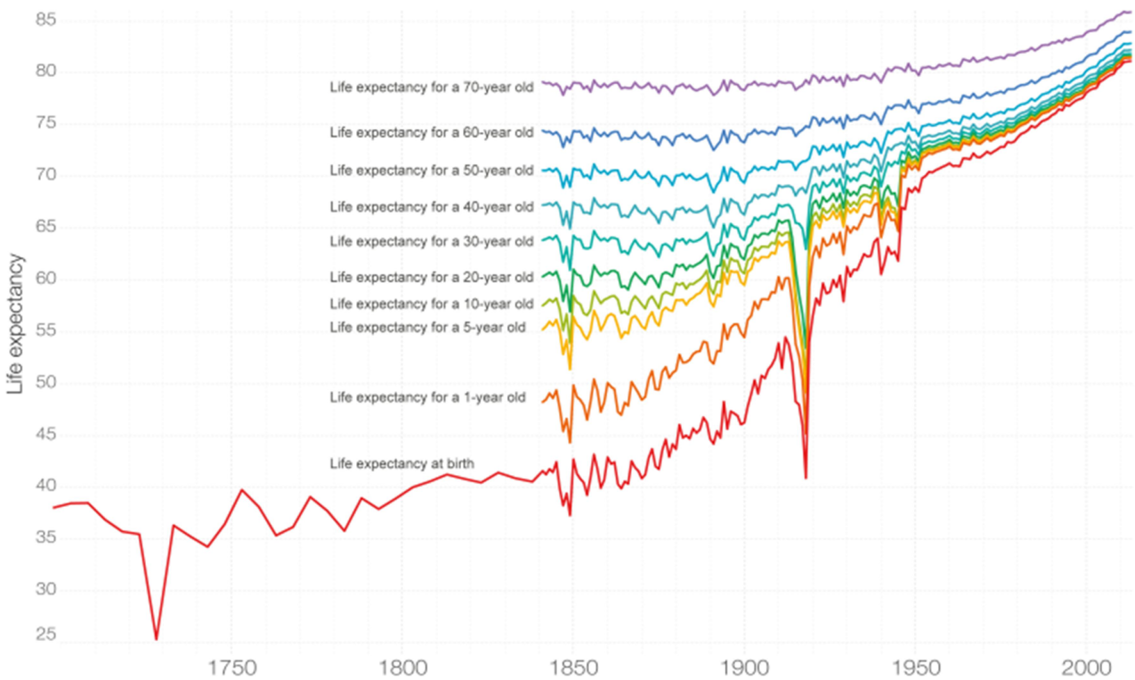


Figure 1.3 Average life expectancy in England and Wales

with acknowledgement to the Human Mortality Database (www.mortality.org)

As these changes gradually transformed and extended human living, the diagnosis and management of low AoA, such as due to presbyopia, became an economic necessity. Scientific assessment of AoA began at the height of the Industrial Revolution, as shown in Section 2.1.

The fundamental importance of that science was underlined by the motto of the Worshipful Company of Spectacle Makers – for centuries the most august body representing spectacle sellers – “A Blessing to the Aged”. This motto, dating from 1629 and still in use, suggests that presbyopia was the prevalent optical concern when presbyopes (and some even younger people with uncorrected hypermetropia) were “the aged”.

In presbyopia the near-vision is typically assisted by wearing “reading glasses”. These are spectacles that add positive (ie converging) optical power to an eye that is in focus for distance vision, by placing an appropriately powered lens in front of it. An emmetropic eye that has completely lost its accommodation (to become fully presbyopic) will see objects at 1/n of a metre equally sharply through a nD lens, where n is any positive rational number.

1.3 Reasons to measure AoA accurately

1.3.1 To reset age norms

This would facilitate the identification of abnormal AoA that may be due to an undiagnosed condition, possibly such as mentioned in Section 2.2. Reference to reliable age-norms could also help monitor diagnosed abnormalities that may be shown to affect AoA. Reliable age-norms of AoA may also assist in the refractive management of visual symptoms.

1.3.2 To improve understanding of neural control of accommodation

Accommodation is largely controlled by the parasympathetic branch of the autonomic nervous system. It is largely mediated through subconscious neural analysis of characteristics of retinal image-blur, as described in Section 1.2.1.1. The manner in which sympathetic innervation may also contribute to efficient focussing over a range of distances could be investigated through its effect on AoA.

1.3.3 To help understand how presbyopia develops

Authorities such as Hofstetter (1944) have sought to produce a first-order expression empirically relating AoA to age. The search for that expression continues in, for example, Castagno *et al.* (2016) Richdale *et al.* (2016) and Ovenseri-Ogbomo and Oduntan (2017) using the traditional push-up method. However, the age-norm data have not validated such efforts well. That, as Castagno *et al.* observe, may be due to measurement difficulties. Those are described in Section 2.4. A single linear relationship is anyway unlikely, if only because of factors including the possible inherent variability of AoA between individuals and/or within individuals.

If the accuracy of the measurement of AoA were improved it is possible that the relationship between AoA and age may be defined more reliably. This could improve understanding of the development of presbyopia, discussed in Section 1.2.2.4.

1.3.4 To facilitate analysis of near-vision efficiency

Viewing larger display surfaces tends to increase visual working distance (Cardona and Lopez, 2015). This avoids scanning through larger angles of gaze. Conversely, smaller detail tends to be held nearer to see it more easily. Therefore small devices crowded with fine detail are likely to be held as close to the eye as is comfortably possible. The increased use of smartphones is therefore likely to have increased working at or near the "near point" (the shortest distance from the eye at which the eye can see an object without blur, where that blur would be due to inadequate AoA). Bababekova *et al*. (2011) have shown that smartphone use increases accommodative demand compared to other common information-displays. Therefore, an individual's AoA may affect their efficiency in using small screens or other fine near-vision tasks, so analysis of visual efficiency for such concentrated near work will require accurate measurement of AoA.

That requirement for improvement in the accuracy of measurement is reflected in current research and clinical attitudes to the measurement, as described in Section 3.1. Improved accuracy could also improve understanding of the variation of visual acuity (VA) with working distance, assist in identifying any possible value of modifying any near-vision spectacle prescription before presbyopia, and help inform a system for prescribing the best spectacles to ameliorate presbyopic symptoms.

Accommodative dysfunction has been observed clinically, for example by Lara *et al*. (2001) who also offered a review of accommodative dysfunction. It may take the form of spasm, inertia, or non-presbyopic insufficiency (such as a side-effect of parasympathetic-blocking medication). Accurate assessment of AoA may help to diagnose accommodative dysfunction and assess and guide potential therapeutic approaches.

1.3.5 To assist in controlling myopia

Therapy for myopia, reviewed by Cooper *et al*. (2012) and Smith and Walline (2015) can affect AoA as reported by Loughman and Flitcroft (2016) in low-dose pharmacological treatment. In optical treatment, this effect was expected by Gong *et al.* (2017) who could not identify it clearly but felt that it could be shown with more precise measurement of AoA.

Various parameters have been studied for a possible link with the development of myopia (Allen and O'Leary, 2006). However, apart from that study, no research was found that sought any correlation between AoA and change in refractive error.

1.3.6 Possible other benefits

AoA is a fundamental optometric measurement, as shown in Section 1.2.1.2. It may be necessary to develop its reliability before further applications of it can be suggested and explored.

1.4 Prevalent method of measurement

The prevalent method of measurement is termed push-up, in which the near point is found when the patient reports that an object brought gradually nearer to the eye cannot be focussed as sharply as when it was a little further away (Millodot, 2009).

The standard instrument for the push-up measurement is the RAF Rule first described by Neely (1956) shown in Figure 1.4 and distributed by Haag-Streit UK. It is a rail just over half a metre in length, with a bifurcated end to be held against the patient's cheekbones. The rail bears a four-faced slider displaying high contrast print that includes numbers and upper and lower case letters and in a range of sizes. Figure

1.4(b) shows the object at its actual size. The slider is not internally illuminated but is printed to present higher contrast than can be reproduced here.

Technique with the RAF Rule, in brief and in general, is as follows. The examiner instructs the patient to report when print on the slider becomes blurred as it is slid towards the eye. When the patient first reports blur, the examiner notes the print's distance from the eye using a scale engraved on the rail.

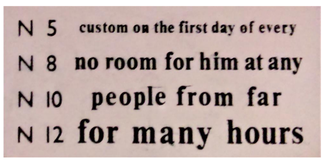


Figure 1.4 The RAF Rule

<u>Upper picture:</u> from the instrument's marketing literature

Lower picture: the face of its slider used in this study

1.5 Aims, objectives and scope of thesis

This study principally hypothesises that a new method of measuring AoA would be usefully more accurate than the prevalent method. The thesis aims to test that hypothesis, by critical appraisal of the literature concerning AoA, and by comparing the trueness and precision of the new method with the trueness and precision of the prevalent method. The objectives of the thesis are; to evaluate the strengths and weaknesses of current methods for clinical assessment of AoA from a literature review; to evaluate the results of measurement with the new method compared to those of the prevalent method and of a standard method; and to discuss the possible clinical value of adopting a more accurate method of measuring AoA in community optometric practice.

The scope of the thesis is as follows. Chapter 2 reviews scientific publications relating to the measurement of AoA and to the reliability of clinical methods of its measurement. Chapter 3 explains the inception of a recent investigation seeking to establish reliability in this measurement. The investigation is detailed in Chapter 4. Its results are reported in Chapter 5 and finally discussed, against the background of the conclusions of the literature review, in Chapter 6, leading to recommendations for AoA measurement in clinical practice.

Chapter 2 Review of the Literature

This literature review set out to assess the quality of the evidence underpinning current methods of measurement of AoA. It is an update of a published review by Burns *et al.* (2014) presented in Appendix 1.

Since that publication, two notable changes have occurred. Firstly, researchers such as Castagno et al (2016) and Gong et al (2017) using the established method of measuring AoA have begun to question its validity. Secondly, the College of Optometrists has lowered the importance it ascribes to the routine clinical measurement of AoA, as discussed in Section 2.1.

This survey reviews reports of the prevalence of AoA measurement, support for measuring AoA, and descriptions of methods of measuring AoA. It assesses the conclusions of publications concerning those methods' sources of error and their precision. It reviews normative studies of AoA and their strengths and weaknesses, and looks at textbooks teaching AoA measurement to students of vision-care.

The strategy for finding relevant peer-reviewed material to appraise critically for this survey of the literature was as follows. Searches for publications were undertaken with PubMed, VisionCite and Google Scholar search engines. Keywords sought, in all fields, were *accommodation OR accommodative AND eye OR ocular AND measurement AND amplitude*, and in Title/Abstract for *accommodation OR accommodative AND amplitude AND age*. In addition to electronic searching, references of possible relevance given in publications reviewed were also reviewed.

Research publications identified by systematically searching as above were appraised, according to CASP guidelines such as those for cohort studies and PRISMA principles, for possible inclusion in this review. PRISMA statistics were not included in the published Literature Review (Appendix 1) on which this update was based as described above. It was found that few research publications concerning AoA would satisfy methodological or other criteria for inclusion. However, those that help to describe the background of current knowledge of AoA are included.

2.1 Measurement of AoA is well established

AoA has been measured in routine clinical eye examination for many decades (Rabbetts, 2007). The measurement and its clinical value were first described by

Donders (1864). Sergienko and Nikonenko (2015) mentioned that there had been techniques competing for almost a thousand years to measure AoA, but they gave no reference supporting that.

However, in 2016 the College of Optometrists downgraded the measurement's importance from general to selective application by adding the phrase "if you feel it is clinically appropriate" as mentioned in Section 1.2.1.2. This may have been a response to the possibility that the measurement as currently practised may have inherent flaws (described in Section 2.4) implying that its reliability was questioned. Nonetheless, no organisation that regulates clinical practice in the UK prescribes any assessment of accommodation other than amplitude.

2.2 The possible value of accuracy in the measurement of AoA

AoA measurement can assist in the optical management of commonplace vision problems such as presbyopia and other spherical refractive errors. Overviews of this subject are generally given within textbooks of ophthalmic clinical science such as those by Barrett (2013) Rosenfield (2009) Rabbetts (2007) and Abrams (1993).

Divers surgical approaches have been developed to restore or replace accommodation. Early progress in this field was reported by Kessler (1964) who reported the successful replacement of lens capsular contents with clear viscoelastic material in rabbits, a technique that Kessler proposed to restore accommodation lost in presbyopia.

A review of current and lapsed surgical techniques to restore accommodation in humans was produced by Gil-Cazorla *et al.* (2016). Accurate and reliable outcome-measurement is necessary, especially considering that the surgery is elective, costly and risky, but the review by Gil-Cazorla *et al.* showed that throughout the world and for many years such surgical adjustment of a normal function appeared to have been offered without reporting validated measurement of that function. The review by Glasser (2008) proposed strongly that measurement be objective, while explaining some challenges presented by current methods of objective measurement. Other reviews such as those by Pallikaris *et al.* (2011) and Bowling (2016a) of surgical techniques to restore accommodation have not compared, or even assessed, methods of making the fundamental measurement.

Of those reviews, the most recent and wide-ranging was that by Gil-Cazorla *et al.* (2016). It addressed measurement of AoA only by mentioning the comment of

Pallikaris *et al.* (2011) that such measurement was difficult, and showed that most studies did not report systematic measurement. The review by Pallikaris *et al.*, in discussing lenticular surgery only, noted that inconsistency between methods used in different studies remained a significant drawback in evaluation of presbyopia-treatment results. It is therefore not surprising that the review by Bowling (2016a) of surgery to reduce refractive error, prefaced discussion of surgery for presbyopia with the remark "correction of presbyopia is yet to be achieved on a consistently satisfactory basis".

In addition to age, a wide range of other factors such as some pathological conditions, and certain recreational and prescribed medications, have been reported to influence AoA. They include refractive error (McBrien and Millodot, 1986), ethnicity or race (Rambo and Sangal, 1960; Edwards *et al.* 1993), adaptation to sunlight (Coates, 1955), climate (Miranda, 1979), urbanisation (Eames, 1961), periocular temperature (Takahashi *et al.,* 2005), dyslexia (Evans *et al.,* 1994) and other reading difficulties (Palomo-Alvarez and Puell, 2008), schoolchildren's visual and ocular comfort (Sterner *et al.,* 2006), intraocular pressure (Dusek *et al.,* 2012), diabetes (Moss *et al.,* 1987), Down syndrome (Woodhouse *et al.,* 1993), hyperthyroidism (Cogan, 1937), alcohol consumption (Campbell *et al*., 2001), premature birth (Larsson *et al.,* 2012), time of day (Somers and Ford, 1983), systemic anticholinergic medication (Rennie, 1993), ocular dominance (Momeni-Moghaddam *et al.,* 2014), ocular surgery (Schachar, 2000), binocularity (Fitch, 1971) and visual axis declination (Ripple, 1952, Atchison *et al.* 1994a).

The significance of these findings is difficult to determine as the possible apparent variations in AoA due to methodology may have been larger that the reported effect. The variations included those due to measurement accuracy as described in Section 2.4, and others for example as follows. In the study by Takahashi *et al.* (2006) all participants were measured cold then warm so order effects may have influenced results. Cogan (1937) expressed doubt that AoA measurement was conclusively accurate, and Schachar (2000) did not declare his non-research interest in his results (which have not been widely accepted). Moss *et al.* (1987) included data from both eyes of participants, a procedure criticised by Ederer (1973) as it would have resulted in an overstatement of the effect found because the results from each of a pair of eyes are invariably correlated with those from the fellow eye and so are not independent. Statistical analysis to reduce that effect were subsequently developed. They were described by Armstrong (2013).

Reliable measurement of AoA might verify, and perhaps accurately quantify, its correlation with age and other factors.

2.3 Methods of Measurement

Methods of measuring AoA are described below and their potential sources of error are then evaluated. They can be principally objective or subjective. Subjective methods make use of the participant's judgement. They are more common, which may reflect their tendency to involve less equipment. Their prevalence may also be partly because refractive error, which is more prevalent than the sum of all other eye conditions requiring attention (according to authorities such as Bourne *et al.* (2014)) is assessed in common clinical practice principally by subjective rather than objective methods.

2.3.1 Objective Measurement

Objectivity in making any measurement decreases the possible influence of bias on the result. The bias can cause error in measurement, and it can arise from the person being measured and from the person making the measurement. Bias due to the examiner can be reduced by automation of measurement, and eliminated by full automation, while bias due to the participant's awareness of the measurement process cannot be eliminated. Fully objective measurement has not been achieved, for the reason described in Section 2.3.1.1.

2.3.1.1 Automated objective refraction

Glasser (2008) recommended automated objective refraction for the measurement of AoA because automated objective refraction could differentiate accommodation, arising from dioptric change, from pseudoaccommodation, arising from optical irregularity and other factors (see Section 3.4). However, it could be argued that objective measurements of AoA should be validated against subjective measurements of AoA as subjective observations can demonstrate the value of the ocular refocusing.

No reports of AoA measurement using automated objective methods in clinical practice were found. Reasons for this absence of research could include that such methods are much more costly and cumbersome than the others described below. The least costly, least cumbersome, most objective, most reported and the best validated technique for this purpose uses an infra-red open-view autorefractor. An autorefractor is an automated device to measure the eye's refractive error, substantively or completely objectively. Open-view autorefractors, such as the instrument used in this study, permit measurement of an eye looking at something else that may be unconnected with the device. They are rarely found outside research laboratories according to Leon *et al.* (2016) and have been recommended for application in objective refraction research, and their use in measuring accommodation described, by Mallen *et al.* (2015) Drew (2013) and Kundart *et al.* (2011).

Fully objective measurement of accommodation has not been reported. It would require all movement to be automated to exclude any influence due to the operator. Measuring accommodation with any commercially produced autorefractor involves some voluntary and involuntary movement as described by Anderson and Stuebing (2014) including continuous re-alignment of the measuring system. A mostly-automated system was produced by Drew (2013). It was more advanced than that used by any other authors as it included automated and programmed movement of the distance of the visual stimulus from the eye. No reports were found of it having been applied clinically or in research.

Autorefractors may be measuring a function that is not quite the same as accommodation although closely related to it, because the effects of other changes in the eye on accommodation may not be the same for the autorefractor's measurement beam as for light normally perceived by the eye. Relevant changes occurring with accommodation, in physical characteristics of the eye, include:

- the effective area of the pupil in the fully accommodated eye can be as little as one-tenth of the pupil area when the eye is unaccommodated, as shown in research such as by Marg and Morgan (1949) while the eye's refracting surfaces' effects vary somewhat idiosyncratically for different ray-paths that may be used by the autorefractor and by the eye resolving fine detail. Autorefractors need a minimum pupil diameter to operate, and it is substantially larger than the minimum required by human vision
- ciliary muscle action may pull the retina to tilt foveal photoreceptors enough to significantly alter their response to light (Enoch, 1975; Singh, 2009)
- changes in optical aberrations of the eye with accommodation would affect the distribution of light within the retinal image of an object point and hence the eye's ability to resolve fine detail. They include chromatic aberration (Atchison *et al.,* 1993) and monochromatic aberrations (Atchison *et al.,* 1995, He *et al.*, 2003, Atchison, 2005, Buehren and Collins, 2006: reports vary, describe large inter-individual variation, and were summarised by Charman, 2008 and Aldaba *et al.,* 2013)
- on accommodation any tilting, or vertical or lateral shifting, of the lens would induce astigmatism which would be partly irregular. This irregular astigmatism may arise from rotational asymmetry, of ciliary muscle action or of tension in the zonule, or of sectorial inhomogeneity of the lens. Its magnitude would be highest on extreme accommodation, but no reports of its investigation at the near point were found. Inter-individual variation

would be likely. That variation could partly explain the evident lack of consensus (Schachar, 2007) regarding its magnitude, although it has long been the subject of enquiry. It is over eighty years since Fincham (1937) observed a lens' downward shift when an eye accommodated fully (the shift being attributed to gravity in looser tethering of the lens by the zonules when the ciliary muscle contracted). More recent work has demonstrated the physical change in tethering of the lens with attempted close-up focusing in presbyopia, such as by He *et al.* (2011) for crystalline lenses and Tabernero *et al.* (2016) for rigid implanted replacement lenses.

These changes would affect the resolution of fine detail so that effective accommodation and autorefractor measurement of accommodation would differ, due to differences (such as of wavelength, position and width) between the perceived ray bundle and the autorefractor's measurement beam. Their effect would be greatest at extremes of accommodation, as in the measurement of AoA.

2.3.1.2 Non-automated objective refraction (retinoscopy)

The optical focus of the eye can be assessed by retinoscopy, a partly objective method in widespread clinical use.   Retinoscopy requires no judgement by the patient. It uses a retinoscope, a small hand-held device to enable the examiner to look along a beam of light from it to the patient's pupil. The examiner assesses the reflection of the beam after its refraction by the eye's optical system, adjusting it with lenses of known power held in the beam until the reflection, known as the reflex, takes a certain appearance, known as reversal.   Retinoscopy is comprehensively explained by Corboy *et al.* (2003) describing it as the established and prevalent clinical method of measuring ocular refraction. It is not fully objective as it relies on some subjective factors including, for example, the clinician's interpretation of the retinoscopy reflex. However, it is not as costly or cumbersome as automated objective refraction.

The use of retinoscopy for the clinical measurement of AoA was described by Wold (1967) Woodhouse *et al.* (1993) Roche *et al.* (2007) and Leon *et al.* (2012). It has been recommended for some patients with substandard visual acuity, by Leat and Mohr (2007) and for those with communication difficulties, by Hokoda and Ciuffreda (1982) and by McLelland and Saunders (2003).

The application of retinoscopy to the measurement of AoA is by stimulating accommodation maximally while the practitioner determines the end-point by interpreting the retinoscopic reflex. This process requires practitioner skill, judgement and experience, according to authors including Wold (1967) Roche *et al.* (2007) and Tay *et al.* (2011) to an extent that may explain why its use seems to have been reported less often than other methods. Glare from the retinoscope beam must be minimised, as in AoA measurement by Wold (1967) and Roche *et al.* (2007).

2.3.2 Subjective Measurement

2.3.2.1 Push-up

The push-up method is “ubiquitous” (Somers and Ford, 1983) and the "commonest and simplest clinical technique to measure AoA" (Atchison *et al.*, 1994b). In this method the patient, optically corrected for distance vision, views a detailed test object slowly approaching the eye and reports when there is “the first slight, sustained blur” (Rosenfield, 2009). The test object is then understood to have just passed the eye's near point and its distance to the eye is measured. The measurement (in metres) is converted to its reciprocal to give the AoA (in dioptres).

This method of measuring AoA appears prevalent in research work, in clinical teaching (Barrett and Elliott, 2003; Rabbetts, 2007) and in clinical practice (Atchison *et al.*, 1994b) as described in Section 2.3.3.

2.3.2.2 Push-down

The push-down method can be considered as a variant of the push-up method which it resembles except that the target is moved away from the patient, from being too near for the patient to resolve, until it can be seen. No reports of its use have given a cogent rationale for choosing this variant.

The criterion for the end-point varies. For example, in its earliest description (Turner, 1958) the test object is moved away from the eye until the patient reports when it first becomes “quite clear” whereas the end-point criterion “sharp and clear” was used in research by Leon *et al.* (2016), “just becomes clear” in research by Benzoni and Rosenfield (2012), “absolutely clear” (Rosenfield, 2009) and “just recognisable” (Barrett, 2013). The latter two authors recommended averaging its results with the push-up method.

The “just recognisable” criterion was first described by Scheiman and Wick (1994) who called it the “modified push-up method” and it has been used in research for example by Koslowe *et al.* (2010) Taub and Shallo-Hoffman (2012) and Chen and O'Leary (1998). The latter authors called it the “modified push-down method” which could be confused with the “modified pull-away method” (Barratt, 2013) the “modified push-down method” of Leon *et al*. (2016) in which the method differed significantly to the modified push-down method of Chen and O’Leary, and the “modified push-up method” (Momeni-Moghaddam *et al.,* 2014) all of which used auxiliary fixed-power diverging trial lenses. Thus the push-down method appears to lack standardisation in nomenclature and in technique.

The number of different end-point criteria mentioned above for the push-down method is in contrast with the single “best clarity” criterion in the literature for the push-up method. This could be because the near point is identified in push-up as soon as best clarity is lost. However, it is less certain in push-down because the target must travel further from the near point to establish that there is no further improvement in clarity, so alternative criteria have been advised for this method.

2.3.2.3 Minus Lens

In this method (Sheard, 1920; Woodruff, 1987) negative spherical lens power is added to the distance refractive correction until the patient cannot maintain the initial acuity at a preset viewing distance well beyond the expected near point. The AoA is given by the maximum power added while the patient can maintain focus, corrected for the viewing distance's vergence.

This method should only be used for monocular measurement and only under monocular conditions. This is because, as mentioned in Section 1.2.1, accommodation and convergence work together, although the link between their operation is not rigid, so the minus-lens method induces much more accommodation than would be required for the viewing distance, causing the other eye to over-converge so that it looks elsewhere; or, if binocularity is maintained, the pre-setting of convergence may limit accommodation. However, unlike push-up and some push-down methods, it only requires the resolution of an object, and so may be easier to manage, for the examiner and for the patient, than reporting whether the object is clear.

2.3.3 Current routine clinical practice

A search of the published literature showed no systematic survey of current routine clinical practice in the method of measuring AoA. However, many authors, eg Goss (1992) assert that push-up is the commonest method (Goss, in a paper reviewing the field of clinical assessment of AoA in the USA, gave no other method). Standardised patient research into the content of routine optometry showed that push-up, and occasionally push-down or a combination of the two, were the most commonly used in England in 2006 (Shah, 2013, personal communication arising from Shah *et al.,* 2008).

The present author analysed 40 email and personal replies from a random sample of practising UK optometrists, mostly via a private email list, in 2000. The survey showed similar results to those of Shah *et al*. Push-up accounted for 68% of measurements in routine practice, and 75% when the exercise was repeated in 2012 with 80 respondents. The methodology was anecdotal, informal, and included no management of possible sampling bias. However, aside from the publication by Shah *et al.* mentioned above, no other evidence was found of current clinical practice in measuring AoA.

2.4 Sources of Error in Methods of Measurement

The literature shows several distinct sources of error in current clinical methods of measuring AoA. They are as follows.

2.4.1 Depth of Focus

In foveal viewing, the eye's Depth of Focus (DoF) is the range of an object's vergence at the eye without any blur being detected (Charman, 2009). It is separate from accommodation. DoF arises partly because of inherent imprecision in optical focussing systems due to diffraction and aberration (Lipson *et al.,* 2010), partly because of any non-inherent imprecision in optical focussing systems, and partly because of limitations to the detection of blur (Wang and Ciuffreda, 2006).

DoF also depends on refractive history as that may lead to adaptation to blur (Cufflin *et al.,* 2007) and may reduce awareness of blur ("neurological and perceptual tolerance" (Wang and Ciuffreda, 2006)) that varies extensively between patients (Atchison *et al.*, 1997) and with viewing conditions (Wang and Ciuffreda, 2006). It affects all of the methods of measuring AoA that require the patient to recognise blur. However, because of its variability as shown above, the contribution of DoF to measurements of AoA cannot be reliably quantified.

Hamasaki *et al.* (1956) were the first to demonstrate that DoF affected AoA measurement. They compared measurements of AoA using the push-up method to those by stigmatoscopy, a technique that used the perceived sharpness of a spot of light to determine the refractive state of the eye. Stigmatoscopy theoretically eliminated DoF (Lancaster, 1934). The magnitude of the results using stigmatoscopy was less than half of those obtained by push-up, and the authors attributed this to DoF contaminating the push-up readings. Their findings were corroborated by Sun *et al.* (1988).

However, the difference may have been due to two other factors. Hamasaki *et al.*'s 106 participants were 41 to 60 years old, so they had little accommodation and nearly half of them were old enough to have had none (Charman, 1989). Therefore their study's findings may be biased by sampling error. Sun *et al.* measured only seven participants. Furthermore, stigmatoscopy is unvalidated and appears to have fewer published reports than all other methods considered here.

Atchison *et al.* (1994b) also investigated the effect of DoF on the measurement of accommodative amplitude, by method-comparison. They compared results with the ordinary push-up method using test objects of constant real height (N5 print) to those made in the same way except with smaller test objects of constant apparent size (as N3 print held at 40cm, which, if upper-case, would have been 25% larger than median threshold resolution at 40cm for their youngest participants, but it was lower-case). Participants' ages were 27 to 45 so the study did not address youthful levels of accommodation, but Sergienko and Nikonenko (2015) measured AoA by the push-up method for younger (age 8 to 25) participants. They also used test-objects of constant apparent size (58% of the maximum height of the text used by Atchison *et al*. but 4-way single Landolt Rings, so relatively legible), and they too obtained results that were significantly lower than established norms. The reduction was of similar degree to that found by Atchison *et al.*

Atchison *et al.*'s results with reduced DoF were around 75% of those with ordinary push-up, and around 55% of those found by Duane (1922). That is a large disparity, even allowing for methodological differences including that Atchison *et al.* drew on results from only 60 participants - far fewer than the 4000 whose results were reported by Duane – and used a visual stimulus of text while Duane used a line stimulus and studied a much wider range of participant age.

Moreover Duane used homatropine cycloplegia to measure the refractive error of many of his participants, whereas Atchison *et al*. did not. Cycloplegia is a temporary reduction or paralysis of accommodation, homatropine being a powerful drug for this purpose (Wolf and Hodge, 1946). The AoA is the maximum increase in the eye’s power so its clinical measurement involves relaxing accommodation as much as possible. Homatropine cycloplegia simplifies that by eliminating most or all accommodation. However, the difference in refraction between an individual’s lowest normal level of accommodation and the level under homatropine cycloplegia is not precisely predictable (and may be substantial) as demonstrated by Nayak *et al.* (1987) who showed that for young, normal eyes without high ametropia, homatropine tended to relax accommodation beyond the lowest normal level by 0.33 D on average.

Nonetheless, the results of Hamasaki *et al.* (1956) and Atchison *et al.* (1994b), described above in this Section, strongly suggest that DoF causes large errors in all of the routine subjective clinical methods of measuring the AoA. In practice, the error may be greater than that found by those researchers because:
- in both studies the method would have reduced but not eliminated DoF
- experimental conditions and participants' expectations differ sufficiently from those of the naive patient in routine clinical practice
- an unknown proportion of both studies' participants may have been trained observers who would have been keener than patients in clinical practice to observe blur,
- trained observers were more likely than patients in clinical practice to have been aware of the purpose of the investigation than patients would be in clinical practice.

If accommodation is measured with any method that requires the patient to recognise blur, the end-point could be anywhere between the degree of defocus that causes minimal blur and a degree that renders the test object indiscernible. The data obtained by Atchison *et al.* (1994b) show an average value below 0.25D DoF for their experimental target, suggesting that their participants tended to interpret “first blur” as when the target was almost unrecognisable despite being firmly instructed to say when first blur was seen.

It has long been appreciated that higher measurements of dioptric power include disproportionately higher errors in the push-up method. This is because the degree of defocus just sufficient to render an object indiscernible is directly proportional to the angular size of the object and inversely proportional to the object's distance from the observer (Jackson (1907); Berens and Fonda (1950); Rosenfield and Cohen (1995)).

To overcome this, Somers and Ford (1983) proposed and assessed measurement with a test object of constant apparent size at different vergences. This was achieved through using a Badal optometer system, as did Ostrin and Glasser (2004) in comparing research methods of measuring AoA, though Stark and Atchison (1994) found that for a minority of participants, and Aldaba *et al.* (2017) for a majority of participants, accommodation is significantly different if stimulated when viewing through a Badal system to when viewing in free space. However, no reference to such use of the Badal system in clinical practice has been found, aside from one long-obsolete device introduced by Lindsay (1954) and mentioned minimally in peer-reviewed literature by Rabbetts (2007, p129). This lack of attention may reflect practitioners' chronic disinterest in AoA described by Coates' comment mentioned in Section 3.1 which may in turn have reflected the weak validity of prevalent clinical techniques for measuring AoA.

DoF inflates measurement of AoA (particularly in methods such as push-up, measuring the distance of an object from the eye). Therefore DoF causes the push-up method to give higher results for AoA than the minus-lens method, as found by Wold (1967), Hokoda and Ciuffreda (1982), Ostrin and Glasser (2004) and Rosenfield and Cohen (1996) although DoF slightly affects measurements with the minus lens technique too (Momeni-Moghaddam *et al.*, 2013). Error due to DoF is maximal in the push-down method using the "just recognisable" end-point criterion, because its end-point is when the test object is as defocussed as it can be without being unrecognisable.

The extent to which DoF causes measured accommodation to exceed true accommodation will be influenced by:

- *parameters of the test object*, such as the luminance, sharpness, contrast, shape, and apparent size of its object's detail for the observer to assess for blur. These factors were described by Tucker and Charman (1975). Kragha (1986) noted that reporting of these parameters varied greatly, in a review of surveys of AoA around the world. Most reports of measurement have specified test-object height only, but Turner (1958) and Atchison *et al.* (1994b) also specified other parameters. However, some investigations cited in other work, such as Eames (1961) and Ayrshire Study Circle (1964) specified no object parameters.

- *The observer's perceptual discrimination.* This itself is the product of many unquantifiable factors including learning, adaptation, motivation, and the eyes' health.

- *pupil size* affects DoF as described by Charman (2009) and (Lipson, 2010). The eye's pupil diameter reduces, allowing greater DoF, with a variety of commonplace factors such as mental effort (Peavler, 1974) age (Winn *et al.*, 1994) and accommodation itself (Marg and Morgan, 1949). Changes of pupil size are caused by these and many other diverse influences (see for example Gilzenrat *et al.*, 2012) the net effect being too complex to allow sufficiently accurate prediction of the effect of pupil size on an eye's DoF.

Few reports of measurement of AoA mention DoF. Duane (1922) was aware of it and stated that it would not affect measurement though did not explain why it would not. Fewer authors have proposed a routine clinical method that attempted to limit the effect of DoF (by reducing test-object size) and fewer still have reported using that principle. Atchison *et al.* (1994b) described such a method and its use. Their method does not appear to have been copied, possibly because it would appear to have been more tedious and complicated than others in use. No reference was made to that method in Atchison's later advice on measuring AoA (Atchison, 2009) in which he described a similar idea proposed for the same reason long before (Berens and Fonda, 1950). The paper by Berens and Fonda mentioned three previous publications by different authors since 1885 that had proposed reducing the size of test-letters to reduce DoF in measuring AoA. That principle, which does not appear to have been criticised in the literature, was applied in work by Allen and O'Leary (2006) and by Atchison *et al.* as mentioned above, but apparently by no other author.

Most measurement of AoA in research reports such as by Sterner (2004) and Adler *et al.* (2013) and in clinical work has been made by participants viewing text optotypes that vary in apparent size, sometimes as much as tenfold. Rosenfield and Cohen (1995) showed empirically that this practice added an erratic amount to the measurement, found that these errors were attributable to DoF, and accordingly suggested that methods be revised. Objective measurement of AoA, with participants viewing patterns whose spatial frequency may be effectively more coarse than that presented by typical optotypes used in other research for this purpose, has been reported (eg Drew, 2013).

In the studies mentioned above that all found higher AoA results with the push-up method than with the minus-lens method, all but one, described below, mentioned DoF as a possible cause. They mentioned that in the minus lens method the apparent size of the test object is reduced in measuring higher accommodation due to greater minification of the test object by the measuring lens, so that DoF would contaminate lower measurements more when using that method, but simple spectacle-magnification calculation shows that the effect would be much too small to account for the disparity in results between the two methods.

The report (Ostrin and Glasser, 2004) that did not give DoF as a possible reason for the push-up method giving generally higher results for AoA than the minus-lens method did mention the possibility for older patients with smaller pupils. Ostrin and Glasser compared five different methods of measuring AoA on 31 participants aged 31 to 53 years, to “study the efficacy” of different methods, partly in response to surgeons’ requirement for validation of elective surgical procedures claiming to restore accommodation. Two of the methods were unusual and were used for a mean of three readings: focometer, and Hartinger Coincidence Refractometer measuring one eye while the other eye's accommodation was maximally stimulated with minus lenses for distance vision. The other three methods were single readings – the Hartinger instrument during drug-stimulated accommodation, push-up, and minus lens. The results showed general large variation between methods, between participants, and within participants.

Experiments by Woehrle *et al.* (1997) also tacitly support the contention that DoF inflates results substantially. Woehrle *et al.* obtained results, for 25 participants aged 10 to 40 years, that were similar with the push-up method to those with push-down, and they cited other studies that found the same effect. The effect could arise because the error due to DoF in push-down to recognition was counter-balanced by the error due to reaction time in push-up. Reaction-time error is described next.

2.4.2 Reaction Time

In the push-up and push-down methods, reaction time causes four additive errors that occur consecutively as the test object moves past the point where noticeable blur (or, in the push-down method, non-blur) first occurs. The first two reaction times are the patient’s and the other two are the examiner’s. They are:

1) the time taken to decide that the target looks blurred
2) the time then taken to vocalise that decision
3) the time then taken to register that message
4) the time then taken to stop the movement.

The duration of (2) in the list immediately above may increase if the patient feels awkward about the test or the clinician, so as to be reluctant to declare that the test object is blurred, or if the patient is used to blur as described by Cufflin *et al.* (2007).

Reaction time may influence results with the minus lens method if the added lens is changed fast enough between noting first sustained blur and stopping changing the lens. Such speed would be possible with a phoropter. However, reaction time is mainly a source of error influencing methods that involve movement of the target.

The error can be limited by reducing the rate of change in test-object vergence, although slower rates of change are less obvious so may make the end-point harder to discern. It increases non-linearly with test-object velocity when measuring accommodation on a scale of distance (Atchison *et al.*, 1994b) as dioptric demand is inversely proportional to viewing distance. At typical maximum accommodation levels, moving the test-object a centimetre represents less than 0.1 D for a forty-year-old but about 1 D for a ten-year-old.

Some authors (eg Rabbetts, 2007; Barrett, 2013; Leon *et al.,* 2016) therefore advise adding a minus lens in the trial frame when measuring high levels of AoA to reduce error caused by the target being very close at the end point. This would help reduce error though not greatly or systematically, and would introduce error due to proximal effects described in Section 2.4.6.

It would therefore be preferable to move the test object at a constant and slow rate of dioptres, rather than centimetres, per second, but that would be difficult to manage without complex automated equipment. Some researchers such as Atchison *et al.* (1994b) Allen and O'Leary (2006) and Sergienko and Nikonenko (2015) adopted the tedious strategy of moving the target in step changes to reduce reaction-time error: the latter authors' participants were children, for whom tedium may cause relative inaccuracy. Evans *et al.* (1994) moved the target at a dioptrically constant rate (0.5D/sec). This strategy would spread reaction-time error evenly over the range of result values but may be difficult to reliably achieve without automation.

Others adopted quite varied rates including 0.4 cm/sec (Somers and Ford 1983), 1 cm/sec (Adler *et al.,* 2013), 2 cm/sec (Castagno *et al.,* 2016) 4 cm/sec (Leon, 2016, participant controlling push-down movement) or even 5 cm/sec (Woehrle *et al.,* 1997; Antona *et al.*, 2009: Koslowe *et al.,* 2010). At 5cm/sec the effect of reaction time on the test result could exceed one-third of their highest reported values. For example, if the near point were at 7.5cm (13.3D) movement might stop at 5cm (20D). Researchers from the earliest (Donders, 1864) to present times (eg Adler *et al.*, 2013; Castagno et al., 2016; Ovenseri-Ogbomo and Oduntan, 2017) obtained values exceeding 20D with the push-up method.

Reaction-time error would be slightly greater for the push-down method, in which clarity is detected, than the push-up method, in which blur is detected. This is because the end-point is registered in push-down when the observer detects that the test object's sharpness stops changing, which requires comparison of sharpness at points after passing the near point, whereas in push-up the observer seeks for the sharpness to start changing, by comparing the sharpness at points before and after passing the end-point, giving an end-point closer to the near point.

However, Atchison (2009) speculated that the push-up method would be less accurate than push-down because it used perception of blur rather than of sharpness. There appear to be no reports of direct empirical support for this contention.

Fitch (1971) Rosenfield and Cohen (1996) and Antona *et al.* (2009) found that results with the push-down method were lower than those with push-up. So did Benzoni and Rosenfield (2012) and Leon *et al.* (2016). The latter authors speculated that the finding was due to the difference in reaction time between the push-up and push-down methods

2.4.3 Measurement conditions

In measuring any function, results with any method of measurement can be affected by the conditions of measurement. Therefore these conditions should be specified, and standardised if possible. In measuring AoA, outcome can be influenced by conditions such as the following. Examples are given from studies primarily of the AoA of large numbers of participants. There has been no standardisation of these or other test conditions.

2.4.3.1 Reference point

A line is the shortest distance between two points, so the points must be specified in giving the length of the line. That length is the prevalent measurement in surveys of AoA as they usually set out to record, principally, a visual target’s position. Unfortunately, the reference point has not been standardised.

Some authors such as Ayrshire Study Circle (1964) and Rutstein *et al.* (1993) did not specify any reference point. Others have measured from the target to different points. For example, Donders (1864) recorded the distance to 7mm behind the anterior corneal pole whereas Duane (1922) measured to 14mm in front of the eye (13mm in his earlier publications on this topic). Kaufmann (1894) and Eames (1961) measured "to the eye" (as Moss *et al.* (1987) approximately did). Turner (1958) referenced his end-point to "the spectacle plane" (without giving its position) as did Woodruff (1987) and Leon *et al.* (2016). Atchison *et al.* (1994b) measured to "the cornea". Anderson *et al.* (2008) and Anderson and Stuebing (2014) specified that they measured to the anterior pole of the cornea. Castagno *et al* (2016) stated that they measured to the participant's forehead and McLelland and Saunders (2003) to the chin. None of those authors gave a reason for their choice of reference point.

These positions, some of which are imprecise, cover a range of more than 20mm. Therefore changing the reference point within the range given in the literature could alter the result significantly at medium levels of AoA and substantially more at higher levels.

2.4.3.2 Monocular or binocular

When not addressing interocular difference, measurement of AoA would generally be of its binocular effect stimulated binocularly, since in everyday life accommodation is normally stimulated under binocular conditions. However, this is not always possible, because of restrictions due to the measurement method as shown, for example, in Section 2.3.2.3.

This raises the possibility of error. Fitch (1971) found that binocular viewing gave higher results but only above age 32. Measurements of one eye or of both together, under monocular or binocular stimulation, may differ by unknown amounts, because:

- binocular visual acuity is higher (Pointer, 2008) which may affect the speed and precision of detection of blur (or its absence) particulary in methods of measurement of AoA that are affected by reaction time which is described in Section 2.4.2

- convergence induces accommodation and vice-versa (Evans, 2009) and binocularity requires a fixed degree of convergence for the object distance. Therefore the amount of accommodation may be influenced by whether the viewing is monocular or binocular

- pupil size changes with convergence and influences depth of focus (Duane, 1922)

- more natural viewing conditions may allow optimal expression of accommodation (Otake *et al.*, 1993) – for example, monocular viewing may cause the participant to feel somewhat disconnected from the task, and proximal effects described in Section 2.4.6 would decrease

- if the AoA of one eye differs from its fellow, binocular measurement is most likely to give the higher of the two eyes' amplitudes.

Researchers' approach to binocularity has varied. For example, Eames (1961) and Kragha (1986) stimulated and measured binocularly, Turner (1958) took monocular and binocular measurements, and Coates (1955) did not record how the measurements were made. Sheard (1920) and Anderson *et al.* (2008) measured monocularly because they used the minus-lens method which, as explained in Section 2.3.2.3, cannot give binocular results. Participants for Ayrshire Study Circle (1964) covered one eye. Rutstein *et al.* (1993) and Leon *et al.* (2012) measured monocularly as they refracted by objective means: no reports were found of any objective method that gave results for both eyes simultaneously.

2.4.3.3 Correction of refractive error

Correction of refractive error before measuring AoA is important because the mean spherical refractive correction must be added to the measurement (and referenced to the same point as it). Furthermore, latent hypermetropia could cause substantial and varying errors.

The type of refractive error may also influence AoA but investigations have not shown the influence to be large or predictable. McBrien and Millodot (1986) set out to report the extent to which AoA and refractive error were correlated. Their 80 participants were aged 18 - 22 years and a mean of push-up and push-down measurements was taken. They found that the sign and degree of refractive error and the manner of onset of myopia affected AoA. The effect was weak (its presentation on graphs with truncated y-axes may have exaggerated it) but supported by their measurements of pupil diameter since their hyperopic participants tended to have smaller pupils, and hence greater depth of focus, yet lower AoA. A similar effect of refractive error on AoA was found by Allen and O'Leary (2006) using the push-up method for a similar participant group. These results suggest that refractive error is a variable that should be controlled in AoA research. However, surveys of AoA have generally not recorded participants' refractive error.

The approach to correcting refractive error has varied between surveys and sometimes within individual surveys of AoA. Duane (1922) used eyedrops to suspend accommodation for the measurement of refractive error including latent hypermetropia except for some participants over age 46. Turner (1958) also did so but only for some participants younger than 20. Neither author explained why they administered a drug or gave any basis for its selective allocation. Its use could be supported by the findings of McBrien and Millodot (1986) implicitly relating latent hypermetropia to AoA.

Correction of refractive error was not reported in the surveys by Coates (1955) Eames (1961) and Ayrshire Study Circle (1964) and its method was less precise than normal methods in the survey by Ovenseri-Ogbomo *et al.* (2012). In the earliest surveys (Donders (1864) and Kaufmann (1894)) the approach to the correction of refractive error was unclear.

2.4.3.4 Definition of the end-point

Definition of the end-point is inherently imprecise in some methods of measuring the AoA. For example, retinoscopy's end-point is particularly imprecise for the accommodated eye. Nonetheless Rutstein *et al.* (1993) described a method in which the end-point, change in retinoscopy reflex quality, required a subjective evaluation of the reflex by the practitioner. That is one possible reason for their substantial inter-examiner variation, of over 20%, in results, on which they do not comment.

Some authors (eg Eames, 1961; Wold, 1967; Sterner, 2004; and Benzoni and Rosenfield, 2012) have reported measurement of AoA by the prevalent methods that involve saying when a target is clear or blurred, for participants who were young enough to make that vague subjective end-point even less precise. Chen *et al.* (2000) claimed to have measured AoA subjectively in children under two years of age. It seems likely that such measurement requires rather more mature participants to attain useful definition of the near point.

In the minus-lens method, the end-point will depend on how fine the focus must be to discern the target, because finer target detail requires more accommodation. Different researchers using the minus-lens method have used different target sizes, corresponding for example to 6/6 by Sheard (1920) and Mohmeni-Moghaddam (2013) 6/6- by Antona *et al.* (2009) 6/9 by Woodruff (1987) and Leon *et al.* (2012) 6/9- by Andersen and Stuebing (2008) 6/12+ by Taub and Shallo-Hoffman (2012) and 6/15 by Leon *et al.* (2016). Some of these would be likely to introduce imprecision of more than

1 D due to depth of focus alone, given the large reduction (and the consequent increase in depth of focus) shown by Marg and Morgan (1949) in pupil diameter at high accommodation levels.

Measurement of accommodation by retinoscopy has generally involved the retinoscope being positioned closer to the eye than the 67cm normal for retinoscopy. Such studies have included those by Hokoda and Ciuffreda (1982) Rutstein *et al.* (1993) Woodhouse *et al.* (1993) Jimenez (2003) McLelland and Saunders (2003) Leon *et al.* (2012) and Leon *et al.* (2016) in which that distance was the outcome measure as advised by Rabbetts (2007) and Roche *et al.* (2007). That technique is likely to be imprecise, for reasons including the following:

- the participant was likely to move
- the examiner was likely to move, independently of the participant
- the examiner was positioned near to the participant, perhaps as near as 10cm or less, so that any error, such as due to movement or parallax, would be a large proportion of the measurement. This error would be reduced by adding negative lenses to the patient's spectacle plane as this would increase the retinoscopy working distance. That may be why this approach was adopted by Wold (1967) but Wold's results do not show more precision than those of other investigations using dynamic retinoscopy
- the trueness of retinoscopy decreases unpredictably when measuring away from the visual axis (Tay *et al.,* 2011) and this error increases with nearness of a fixed-size target displacing the retinoscope beam
- the measurement was taken some time after reaching the end-point
- the measurement would have included error due to parallax since the ruler had to be held away from points to which it measured, as was well illustrated photographically in the reports that showed this detail
- the measurement end-point involved the subjective judgement of retinoscopic reflexes that were particularly unusual due to changes in ocular aberration on accommodation as described by Aldaba *et al.* (2013)
- the precision of retinoscopy is substantially improved by increasing the working distance (Corboy, 2003; Atchison, 2009) whereas working distances in this technique have been unusually small.

Nonetheless, Leon *et al.* (2016) found excellent reproducibility for this technique. In their study, ten examiners measured fourteen participants' AoA, using additional trial lenses to keep the measurement range between 14 and 67 cm. They found that 95% of the measurements were within 7% of each other. On the other hand Rutstein *et al.* (1993) recorded low reproducibility, with results differing by over 20% for the same participants and procedure, in a smaller study reported in less detail.

All clinical methods for measuring AoA except the minus-lens method principally involve recording an end-point by measuring a distance. No measurement technique is perfectly accurate so there will be some error in pinpointing the end-point. The length of the error is largely independent of the length being measured. Therefore, end-point error is a higher proportion of the measurement when higher levels of AoA are measured. Fortunately, in clinical measurement of AoA, accuracy at lower levels tends to be more important than accuracy at higher levels. It can be argued that an AoA of about 4 D (though more for hypermetropes reluctant to wear refractive correction) would cover almost everyone's practical needs. On the other hand, accuracy in higher values may be useful in identifying change, interocular difference, or outliers, of possible physiological or pathological significance. Research has not yet identified a level of accuracy that might achieve these goals.

In exploring the depth of field of the accommodated eye, Bernal-Molina *et al.* (2014) concluded, "the main purpose of accommodation is not to maximize retinal image quality but to form one that is good enough". However it could be argued that "good enough" is a flexible and unclear concept, and that an adequate level of quality in discrimination tasks cannot be set unless higher quality can be assessed.

2.4.4 Instrument error

The prevalent instrument for measuring AoA, the RAF Rule, is described in Section 1.4. There appear to be fifteen sources of error, listed below, in the design and production, as opposed to the application, of this simple instrument. Each error source has the potential to cause clinically significant error. The resulting errors can all be additive. Their overall effect could be addressed by revising the design although it has not changed in over sixty years since its earliest descriptions such as that by Neely (1956). Other accommodation rules that have been disseminated for clinical use are currently rarely used, to this author's knowledge, and may be expected to share some of the sources of error. Those sources of error are listed as follows:

1. ambiguity about which part of the slider is the index
2. ambiguity regarding which scale-graduation (or neither) the scale's numbers describe, because each number is equidistant between two graduations and indicates neither
3. uncertainty about the location of the scale's zero point, as RAF Rules appear to vary in the distance of any particular scale graduation from the cheekrest, as shown in Figure 2.1 which depicts the first two RAF Rules sourced randomly by the author

Figure 2.1 Two RAF Rules, showing position of scale differs

4. the slider's opaqueness, obscuring interpolation between graduations
5. the effect on the location of the scale arising from inter-individual differences in facial anatomy, at any given distance, d, of the cheekrest below the corneal vertex
6. the effect of not specifying d, mentioned in point (5) above, as facial anatomy is not perpendicular to the RAF Rule
7. the effect of not specifying d, mentioned in point (5) above, as facial anatomy varies between people
8. the effect of not specifying the distance d mentioned in point (5) above on point (14) below
9. the lack of integral standardised luminance contrast, such as by internal illumination
10. the limits of the scale. Principal authorities on AoA (eg Donders, 1864) have reported that it reaches higher levels than the instrument covers. Evans *et al.* (1994), Chen and O'Leary (1998), Sterner *et al.* (2006) and Ovenseri-Ogbomo *et al.* (2012) are amongst researchers whose data may have extended beyond the unmodified instrument's range of measurement, requiring the imprecision of extrapolation.
11. the variable location of fixation within one line of target print, since different letters in the line, which is 27mm long, are at different distances from either eye, producing differing accommodative demand of up to 0.25 D when measuring about 6 D of accommodation with the RAF Rule, higher errors occurring at shorter target distances
12. the effect of target detail size, through depth of focus as discussed in Section 2.4.1
13. the effect of scale interval linearity, through reaction time as discussed in Section 2.4.2.

14. the variability of rail declination. This is shown in Figure 2.2, two pictures taken at random of the instrument in routine clinical use. Taking typical values at the accommodation levels measured, by trigonometry (see Appendix 2) the patient in Figure 2.2 tilting the Rule down would appear to have just over 1 D more AoA than the other patient due only to the tilt of the Rule

Figure 2.2   RAF Rules in normal use, showing error due to declination

Guidance about how to hold the instrument is incomplete and it varies as between, for example, Keirl and Christie (2007) Rabbetts (2007) and Barrett (2013) wherein the RAF is shown tilted substantially down in use. The angle of declination of view may affect AoA, as mentioned in Section 2.4.4.

15. The other source of error inherent in the design of this instrument is relatively systematic. It is that measurements with the RAF rule are always on the midline, which is less than the distance to the eye, as shown by Fitch (1971). This would inflate results by an amount that can be trigonometrically estimated as about 5% at the highest levels of AoA and approximately proportionately less at lower levels, so it is not as large as some other errors listed above. Turner (1958) corrected approximately for this source of error, Fitch (1971) and McBrien and Millodot (1986) corrected for this source of error carefully, while Sterner *et al.* (2006) did not correct for it although reporting a higher measurement range.

In the above list of sources of error arising from apparent weaknesses in the design and production of the RAF Rule, published information was not found for items 1 to 13.

Measurement with the minus-lens technique minifies the target more at higher levels of measurement. This has been cited by Antona *et al.* (2009) and Rosenfield (2009) as a possible source of error. No theoretical or empirical reports were found of the error's amplitude being significant. It is slightly contradicted by the finding by McBrien and Millodot (1986) that AoA was the same with the minus-lens technique as with the average of push-up and push-down to clarity.

2.4.5 Examiner bias

This is a source of error in any measurement that is not fully automatic. The practitioner examining the patient will often, and perhaps always, have an expectation of approximately where the measurement end-point should be. That expectation, and inevitable differences in technique between practitioners, may influence how the measurement is taken (e.g., target speed), which may in turn influence the result. It may affect naive patients more.

Research of accommodative response (Stark and Atchison, 1994) and in fixation disparity (Karania and Evans, 2006) has shown that the exact wording of instructions can influence the results of measurement. Adler *et al.* (2013) found a significant difference between five different examiners' results for push-up measurement of AoA and attributed this to examiners' measurement technique possibly differing slightly.

Examiner bias may be suspected particularly when the general level of methodological rigour appears low and the results are not corroborated elsewhere. For example, the survey in South Africa by Coates (1955) specified no method and discussed the conclusion that AoA was racially ordered. Eames (1961) found a 5 D difference between amplitudes of accommodation of urban and rural children aged five to eight, using a method described only briefly and in unspecific terms.

2.4.6 Anomalous proximal cues

In comparing methods of measuring AoA, the test object is further away in the minus lens method and measurement conditions are monocular, reducing awareness of proximity. Other methods indeed give higher results, to differing extents comparing the results of Wold (1967), Hokoda and Ciuffreda, (1982), Rosenfield and Cohen (1996) and Antona *et al.*, (2009). The lowest values of all investigations of AoA were obtained by Anderson *et al.* (2008) using the minus-lens method with objective measurement (simultaneous autorefraction).

Momeni-Moghaddam *et al.* (2013) found that results for AoA with the minus-lens method were significantly higher when using a shorter viewing distance. Measurement was monocular so the difference was not attributable to the induction of extra accommodation by extra convergence. The authors attributed the effect to proximal accommodation.

Fitch (1971) with particularly careful methodology found that accommodation measured with either the push-up or the push-down methods was higher when the participant grasped and guided the target than when the examiner did. No reason for this finding has been demonstrated but it could have been due to various psychological factors including increased awareness of proximity when the participant connected with, and controlled, the target.

2.4.7 The effect of effort

Methods of measurement that reward patients striving to improve their performance by feeding back how well they are achieving discernment of detail, encouraging effort to achieve the best visual performance, tend to give higher results for AoA and other aspects of accommodation as demonstrated by Winn *et al.* (1991) and Gray *et al.* (1993). Encouragement of effort is advised for even the most basic subjective assessment of eyesight (eg Elliott and Flanagan, 2013).

The power of the feedback differs in different methods. For example, push-down with the "just recognisable" end-point, and the minus lens method, offer the discovery of letters, perhaps a more compelling motivator than the push-up method's goal of nearness (which unfortunately induces extra error as shown in Sections 2.4.1 to 2.4.5) whereas retinoscopy may present no reward for effort.

2.4.8 Summary of Sources of Error

Many, varied sources of error have been described in this Chapter and are listed in Table 2.1. Some produce errors of higher magnitude than others. Some are relatively systematic while others are of unpredictable size or direction or both. Some affect lower readings more than higher readings, and vice-versa. Some methods of measurement are more affected by some sources of error than others (as shown in Table 2.1). Some can be reduced by better attention to technique. Their overall effect considerably reduces the validity of clinical results with current methods.

Table 2.1 Sources, with their Section references, of error affecting the measurement of AoA by the RAF Rule and by the TRU (another method of measurement, introduced in the next Chapter)

Inherent sources of error		Possible sources of error
RAF Rule	**TRU**	**all methods**
Depth of focus 2.4.1	Letter height step size 6.6.4	Reference point eg corneal apex 2.4.3.1
Reaction time 2.4.2	Parallax 6.6.4	Whether binocular or monocular 2.4.3.2
Definition of end point 2.4.3.4	Novelty 6.7.1.1	Whether refractive error corrected 2.4.3.3
Tool design (15 items) 2.4.4		Feedback from achievement 2.4.7
		Examiner bias 2.4.5

2.5 Precision of clinical methods

The limitations outlined above of measurements of accommodative amplitude are likely to limit the precision of these methods. In this Section, studies that have reported method precision are described, starting with those that compared methods.

Three studies were found that compared the precision of different methods of routine clinical measurement of AoA, using similar young adult participant populations. They were by Antona *et al.* (2009) Rosenfield and Cohen (1996) and Leon *et al.* (2012). In such comparisons, methods that give lower values for AoA can be expected to give proportionately lower dioptric values for a given level of agreement.

Antona *et al.* (2009) measured the push-up, push-down (end point of simply identifying letters, of height 0.6mm) and minus lens methods twice in 61 participants aged 18 to 32. They stated that each method involved one examiner, but a different one for each method (masked to each other's findings) and that repeated measures were in a separate session (without stating the interval between the two sessions). Those factors may have introduced some influences of inter-examiner difference, and of reproducibility between sessions, alongside repeatability. The authors concluded that the minus lens method had the best precision, and that the push-up method had the worst, giving 95% limits of agreement ± 4.76 D for participants whose AoA was only about double that.

The precision of the same methods was also assessed by Rosenfield and Cohen (1996) with 13 participants aged 23-29. Their push-down end-point was that the smallest letters that could be resolved at 40cm were absolutely clear. They measured the AoA five times, without stating whether all by the same examiner, but on five different occasions of unspecified separation, for each participant. Those factors may have introduced some influences of inter-examiner difference, and of reproducibility between sessions, alongside repeatability, as for the study by Antona *et al.* described above. They found precision three times better than Antona *et al.* and similar for all three methods, and from their results recommended that changes of less than 15% should be considered statistically insignificant.

Leon *et al.* (2012) set out to assess the reliability of the minus-lens, push-down (end point: letters, 0.9mm high, sharp and clear) and dynamic retinoscopy methods, with two experiments. In one, the AoA was measured for 79 participants aged 18-29 (average, 20) by two examiners in one session. In the other, 76 similar participants underwent the same measurements which were repeated by a single examiner (possibly the same one) at least a week later. Comparing their results to those of the above study by Antona *et al.*, they found that measurement reproducibility was more than twice as good for the push-down method, and also better, but to a lesser extent, for the minus lens method. They found that dynamic retinoscopy was the method with the best reproducibility. However, their method for dynamic retinoscopy involved near point measurement using a metre rule between remote mobile points several seconds after the end-point was reached, so its precision may have required validation.

In addition to those three studies of precision, other studies such as those below have assessed the repeatability and/or reproducibility of single methods. None of them stated that the same examiner repeated all measurements.

Adler *et al.* (2013) measured 120 participants aged six to ten by push-up on three occasions, sometimes with different examiners for each participant, finding that 95% of participants' measurements varied by up to about a quarter of the mean AoA measured. The average measurement was 19D and frequently exceeded 20D, substantially higher than shown by similar measurement such as those of Eames (1961) and Sterner (2006). Measurements may have included particularly high levels of pseudoaccommodation and other errors due to the free-space methodology.

Brozek *et al.* (1948) measured six participants in six separate sessions by the push-up method, possibly using different investigators. Their participants were trained observers and a mean of three readings was taken for each measurement: both of those factors would be expected to give better repeatability than in normal clinical work. Review of their data shows that 95% of their measurements were within ±11% of the mean for that participant, and half were within 4.5%, while reproducibility between sessions varied more than threefold across participants. It is noteworthy that after seventy years this small study of AoA still appears to remain alone in having set out principally to assess the precision of the prevalent clinical method.

Precision of the minus lens method was reviewed by Mohmeni-Moghaddam *et al.* (2013) who measured 43 participants, aged 18 to 24, twice. The report does not state how many investigators were involved, or the time between sessions other than that it was at least 24 hours. Good intersessional agreement was obtained (95% confidence limits circa ±0.83D) whether the target was at six metres or 40cm.

Using the Push-Down method Chen and O'Leary (1998) measured twice in 18 participants aged 18 to 19. They did not state the interval between measurements of each participant or whether the same examiner made the measurements, and they found so little difference between the two occasions that it could be interpreted as negligible.

Overall, studies of precision of clinical methods of measuring AoA have not demonstrated good repeatability, particularly for the more popular methods that involve the participant identifying the moment when a subtle change occurs in the appearance of a moving target. However, it is difficult to conflate their conclusions due to differences in their methodologies.

2.6 Normative studies

Fourteen studies that surveyed normative values for AoA in predominantly Caucasian locations at different ages were found, and are summarised in Table 2.2 excluding others for one or more of the following reasons:
- they did not cover a broad range of the principal cause of variation, participant age
- their participants were known to mainly be non-Caucasian
- they had measured less than 100 participants
- they had not been subject to peer-review
- their methodology might be difficult to reproduce, such as in the study by Woodruff (1987) who reported AoA measurements (up to 19D) from an unspecified reference point of measurement using the phoropter minus-lens method for each eye of participants aged three to eleven in 0.25D steps each requiring six responses.

Table 2.2 Key studies that included population data on AoA

Author	Published	Method	Number of eyes or participants	Participants' age (years)	Main factors that may influence reliability
Donders	1864	Push-Up	130 participants	10 to 80	No assessment of refractive error
Kaufmann	1894	Push-Up	400 eyes of all participants	5 to 74	No assessment of refractive error
Jackson	1907	Push-Up	Most eyes of 3346 participants	5 to 70	Retrospective, some refractive error assessment
Sheard	1920	Minus Lens	Several hundred eyes	15 to 40	Object at 33cm
Duane	1922	Push-Up	Most eyes of about 4000 participants	8 to 72	Refraction largely cycloplegic
Jackson	1922	Minus Lens	Unknown	10 to 65	Binocular
Clarke	1924	Push-Up	Most eyes of over 5000 participants	10 to 65	Retrospective, used Duane's method
Coates	1955	Push-Up	3171 eyes of about 1700 participants	10 to 80	Retrospective, no assessment of refractive error
Turner	1958	Push-Down	About 1000 eyes of about 500 participants	10 to 75	Retrospective, some cycloplegia
Ayrshire Study Circle	1964	Push-Up	1307 participants	30 to 75	Limited details of methodology
Fitch	1971	Push-Up & Push-Down	110 participants	13 to 67	Methodologically relatively meticulous and not intended as normative survey
Bruckner	1986	Push-Up	115 participants	6 to 61	Participants measured over twenty years
Anderson *et al.*	2008	Open-field autorefractor & Minus Lens	140 eyes	3 to 40	As for Fitch above
Leon *et al.*	2016	Retinoscopy, Push-Down to just legible, & Minus Lens	1298 eyes	5 to 60	As for Fitch above

This Section discusses how the studies shown in Table 2.2 are mostly irreconcilable with each other, regarding procedures or results. This difficulty of aggregating studies was shown by Allen and O'Leary (2006) summarising several reports to explore the relationship between AoA and refractive error. Insufficient agreement was found to reveal any such relationship, amongst studies that had used the push-up method. That could be due to that method's poor accuracy, summarised in Section 6.1.

Early investigators tended to use dot or thin line test-objects (possibly due to literacy being less common then) but the relative merits of letters and lines for this purpose have not been reported except for children by Wold (1967). The early surveys, and some later ones, tended to lack participant and experimental detail. For example, in the groundbreaking work by Donders, participants covered the widest age range but were not otherwise described. Duane (1922) in an otherwise careful large-scale fifteen-year research study also did not describe characteristics (such as gender, ethnicity or refractive error) of his very large number of participants.

Nonetheless, Duane's study gives the most commonly cited reference values for the normal range of AoA. Duane's results are the reference values printed on the most common (at least in the UK) instrument for measuring AoA, the RAF Rule. "Accommodation rule" is included in the list of twenty principal items of clinical equipment required for routine eye examinations in the UK (College of Optometrists, 2016) and the RAF Rule, bearing Duane's results, is the only accommodation rule marketed in the UK. Furthermore, Duane's paper was the 59th most cited of all peer-reviewed clinical ophthalmic papers published globally before 1950 (Obha and Nakao, 2010). Table 2.3 shows that, in optometry teaching, Duane's results (and those of Donders) are easily the most-quoted reference values for AoA.

Table 2.3 Methods that textbooks of clinical vision science give for measuring AoA

Author and year of publication	Main method recommended	Other methods described	Object height recommended	Norms given
	key below table			
Abrams 1993	PU	R	none	none
Barrett 2013	PD	M PU	20/30	Sheard, Duane, Donders
Bowling 2016b	PU	M	none	none
Grosvenor 2007	PU	M	N4 approx	Donders
Keirl & Christie 2007	PU	PD R (PU+PD)/2	slightly larger than N5	unattributed
Rabbetts 2007	PU	B M PD R	none	Duane
Reading 1988	PU	M R	none	Sheard, Duane, Donders, Turner
Rosenfield 2009	PU	B M PD R (PU+PD)/2	none	Donders, Duane

B = Badal optometer, M = Minus Lens, PD = Push-Down, PU = Push-Up, R = Retinoscopy

Duane's sample size was more than thirty times that of Donders (1864) whose results were presented unclearly (Hofstetter 1944; Fitch 1971) which may be why an appraisal of these results (Fitch 1971) found that values attributed to Donders often differed significantly. This persists, as some current textbooks of optometry give substantially differing values for Donders' results eg Barrett (2013) compared to Rosenfield (2009). Other values given by Reading (1988) appear to represent Donders' results best.

Jackson (1922), Sheard (1920) and Anderson *et al.* (2008) used the minus lens method, with measurements taken objectively in the latter study. Jackson's work included few experimental details but the method was binocular. This binocular viewing may have significantly lowered AoA results owing to convergence's relationship with accommodation as described in Section 2.3.2.3, yet Jackson's results are higher than Sheard's monocular results. On the other hand, no description of Sheard's body of participants appears to be available except that Rambo and Sangal (1960) report a personal communication from Sheard that his participants were "Middle European". Neither Jackson nor Sheard appeared to have submitted their research to peer-review, which was less commonplace at that time.

The study by Bruckner *et al* (1987) used Duane's technique but was unusual in that monocular results from both eyes were averaged and that the same 115 participants were measured over a twenty-year period, giving 812 measurements. The results appear most similar to those of Duane.

Methodological limitations are often apparent in older work and this may explain the common reporting of a curiously stable and clinically substantial residue of accommodation never lost to age. Methodology developed and it is now generally accepted that most people have completely lost the ability to accommodate just after age 50 (Charman, 1989).

The survey of AoA by Turner (1958) appears to have been the first to standardise the test object's luminance contrast. Johnson (1976) demonstrated that the near point receded with decreasing luminance. The survey by Turner was also the first to use the push-down method (in a survey, though Rambo and Sangal (1960) cited earlier reports of it). For convenience, measurement was to the spectacle plane of the 500 participants. Reaction-time error using the push-down method could account for the results for AoA being slightly lower than most, though on the other hand the particularly large test-object detail used by Turner could have made the results seem higher, as shown by Rosenfield and Cohen (1995) and Atchison *et al* (1997).

Turner used the data from each eye of almost all participants, as did Woodruff (1987). The pooling of both eyes' data in statistical analysis was criticised in Section 2.2. Like Duane (1922) and Clarke (1924) who used a similar method to Duane's, Turner used eyedrops in some younger participants to eliminate accommodation for refraction before measuring accommodation. For this purpose he chose homatropine, a drug that takes several days to gradually wear off (Wolf and Hodge, 1946). As in the other studies that used cycloplegia, it is unclear whether the drug remained active during the subsequent measurement of accommodation.

Ayrshire Study Circle (1964) measured 1307 eyes. This survey's limitations included little description of methodology, variable methodology, lack of refraction (participants wore their distance spectacles, if any) lack of statistical analysis, absence of references, author anonymity, limited age-range as the participants were all over age 30, and errors described above as inherent in the basic push-up method. Its results were unusual in finding that AoA showed gender differences. Meta-analysis by Hickenbotham *et al.* (2012) found no evidence for gender influencing the onset of presbyopia through AoA.

Participant characteristics should be considered when assessing the results of measurement studies. However, normative studies of AoA have shown quite varying levels of reporting of participant characteristics. Some, but not all, of the studies shown in Table 2.2 described participants' race and, more often, gender. This inconsistency makes it difficult to pool these studies' results (Allen and O'Leary, 2006) and, with studies' methodological flaws such as discussed in this Section, may explain why different studies' results differ substantially for participants of any age. However, the effects of participant characteristics such as race and gender on AoA are not known, due to inaccuracy, discussed in Section 2.4, in normative studies' measurement methods.

For example, the AoA results of Donders as reported by Reading (1988) are about half as large again as those of Turner (1958) at almost any participant age despite both having large numbers of participants, using cycloplegia to assess some refractive error, and being relatively thorough. Results still lower than Turner's were obtained by Anderson *et al.* (2008) and, with different methodology, Leon *et al.* (2016).

The latter two studies supported previous contentions and findings that subjective methods have greatly overestimated AoA. Anderson *et al.* measured AoA in 140 subjects aged 3 to 40 using automated objective refraction, accommodation being stimulated by minus lenses using a target at 33cm. Leon *et al.* measured AoA in 1298 participants aged 5 to 60, comparing three different established clinical methods. One of the three methods, retinoscopy, was partly objective. It gave results substantially lower than the two subjective methods (minus lens and push-down) and that, if adjusted to the same measurement reference point (the corneal vertex) agree closely with those of Anderson *et al.* mentioned above.

Differences in the studies' results could be due mainly to differences between their methodologies particularly with respect to test object parameters and movement, use of cycloplegia, and characteristics of the participant group. The results of Millodot and Millodot (1989) for participants over age 39 are several times larger than the age-matched results of Hamasaki *et al.* (1956) using quite different methodology though both studies used non-cycloplegic refraction and their participant groups matched well. In mitigation, neither study's primary aim was to survey normative values of AoA, and both studies acknowledged that depth of focus could account for much of the difference between the values of AoA that they found for a given age.

Table 2.2 shows large variation between studies' sample sizes. None of the studies appear to have been supported by a sample size calculation. Large sample size improves accuracy and may give more information when analysed statistically. Hamasaki *et al.* (1956) were the first investigators who, in measuring AoA, included statistical analysis of their results (beyond mean, highest, and lowest values for age). Hofstetter (1965) and Ramsdale and Charman (1989) described meticulous and deep analysis of their data but for only two and one participants respectively.

Hofstetter (1944) made a thorough comparison of the three major early studies (Donders, 1864; Kaufmann, 1894; Duane, 1922) in an attempt to provide definitive normative data that would give a first-order equation of age and AoA. The studies all used push-up line test-objects but there were some methodological differences between them. However, even taking those differences into account, Hofstetter was not satisfied that the results of Duane could be reconciled with those of Donders (but noted that Kaufmann's results may have replicated those of Donders quite closely). He nonetheless concluded by presenting a linear expression, derived from Donders' and Duane's results, as a guide to the decline of accommodation with age. This expression is still taught, for example in Rosenfield (2009) and Barrett (2013).

The search for that simple and reliable relationship between age and AoA has been further confounded by recent studies. Anderson *et al.* (2008) Anderson and Stuebing (2014) Benzoni and Rosenfield (2012) and Leon *et al.* (2016) all produced measurements that did not support the possibility of a linear relationship. However, considering the accuracy and validity of the methods used in the research as reported in this thesis, and that the research has not shown the extent of short-term variation of AoA within individuals, there is only one confirmed relationship. AoA, like childbearing and possibly no other adult animal autonomous function, decreases to zero well before a State pension becomes payable.

Further research on normative values should use standardised methods as discussed in Section 6.7.3. Possible influences of patient-parameters on AoA may be reviewed empirically after the revision of normative values. That revision would require control of participant characteristics.

At the time of writing, in peer-reviewed journals at the forefront of research into normative values of AoA, the two most recent publications (Hashemi *et al.*, 2016, and Ovenseri-Ogbomo and Oduntan, 2017) report population surveys of AoA measurement with the push-up technique using the RAF Rule. During the writing of this review, that method has generally been the method used in contemporaneous research sometimes acknowledging its inadequate repeatability, for example Gong *et al.* (2017).

Furthermore, the AoA measurement techniques reported in the earliest publications, and those closely derived from them, appear resilient as they resemble currently-taught techniques. The present author emailed the nine UK optometry-teaching departments on 21/4/13 asking how they taught AoA measurement. Four universities responded, of which three taught averaging push-up and push-down and one taught push-down to recognition.

2.7 Conclusion of literature review

The evidence underpinning current methods of measurement of AoA is weak. AoA is a fundamental optometric measurement but the literature shows methodological sources of substantial inaccuracy in its routine clinical measurement. This inaccuracy, and the ranges found in the literature of normative values of AoA, call the values into question.

A new method of AoA measurement is described in the next chapter. If the new method were shown to have fewer of the sources of error identified in this chapter as associated with methods in current use, it would potentially be more reliable.

The potential improvement in reliability is explored empirically in the following chapters. Its extent would suggest whether the validity of normative values of AoA could be reassessed and improved by adopting the new method of measurement of AoA.

Chapter 3 Principles of the Experimental Design

In this chapter, the lack of AoA measurement in routine clinical practice is considered. The measurement is defined, a new method for making the measurement is introduced, and a plan for experimental assessment of the new method is summarised.

3.1 The Possibility of Improving Measurement of AoA

Coates (1955) began the report of his survey of AoA by making the following assertion: "With many of us the rule for measuring amplitudes is apt to gather dust in some corner of the test-room". That neglect of AoA measurement did not change, according to standardised patient research by Shah *et al.,* (2008) showing that accommodation was measured in routine clinical practice by only 36 of 100 randomly-selected optometrists examining a patient for whom measurement of AoA would appear to have been particularly relevant. Optometrists were less likely to record "accommodation" than other tests, and a record of “accommodation” may have related to a casual and imprecise assessment, according to Shah *et al.* (2009). The author of the present thesis worked in many diverse consulting rooms and formed an unaudited impression that equipment for measuring AoA often appeared neglected, as Coates (see above) suggested 62 years ago.

This dilapidation of measurement could be for any or all of the following reasons:

- it takes too long to do it properly
- its accuracy appears inadequate to the graduate clinical scientist
- often it can be adequately replaced by a casual assessment such as a check that small print can be read if held close enough
- normative values lack standardisation and/or credibility.

Surgeons also appear to lack suitable methods of measuring accommodation, as shown in Section 2.2. Reliable and accurate measurement of AoA would be of value, especially considering the risks of new procedures in ocular surgery.

It would therefore not be surprising if many clinicians in the main eye-care professions would find a more reliable method of measuring AoA to be useful. This contention would be supported by the observation that a review of AoA measurement (Burns et al., 2014) has attracted quite high levels of interest as shown by its whole-term and continuing average of about ten reads per week in ResearchGate, “the largest academic social network in terms of active users” (Wikipaedia, 01/05/2017) although it was not indexed by Medline, and ResearchGate had no other submission from the lead author.

Since starting clinical training, the present author felt that the benefit of improving accuracy in the measurement of AoA should be explored. Therefore in routine primary-care optometric practice he tried smaller, simpler, higher-contrast test objects than were in general use for the push-up measurement of AoA, because of the degree to which factors such as depth of focus and lack of test-chart standardisation evidently contaminated the measurement. He found no suitable equipment produced for this purpose. The Priegeltest, described by Vos *et al.* (1994) was the most suitable, and had achieved commercial production, but its test characters were unfamiliar, poorly printed, unchangeable, and too large. This led to the development of new equipment, described in Section 3.5, based on the Threshold Resolution principle described in Section 3.3. Prototyping of this new equipment led to proposed redefinitions of the near point and of AoA, discussed in Sections 3.2 and 3.4 respectively.

3.2 The near point

Defining AoA usually uses the concept of a near point (eg Barrett, 2013; Millodot, 2009; Rosenfield, 2009). It has been suggested (Edgar, 2015, personal communication) that the term “near point” is a simplification because the eye has significant depth of field so the “near point” is not a point but a range. This range would be the distance between two points on the visual axis between which the smallest object can be resolved. It would represent a smearing of the theoretical near point.

The extent of the range would appear to depend on many factors. Some of the factors (such as aberration, toricity, asphericity, pupil size, diffraction, and diffusion) arise in the eye. Others include the size, luminance and luminance contrast of the object. Some are interconnected, to differing extents, and others’ effects may vary for different eyes and visual tasks. Therefore the range of visual distances within which a small object can be seen cannot be easily quantified. However, it can be minimised, as follows.

Consider an eye accommodating to resolve a simple visual object. When the object is large enough, the range for that object is large. Decreasing the object’s size, while keeping all other characteristics of the object constant, will reduce the range (because moving the object near enough to the eye would put it out of focus, and moving it sufficiently further away would reduce its subtense beyond resolution) until the object is too small to resolve at any distance. Thus the range decreases with decreasing object size, while increasing object-clarity eases detection tasks and so improves demarcation of the range. Therefore the range is minimal when the resolvable object is of minimal size and maximal luminance contrast.

Nonetheless the concept of a near point rather than a range remains valid because, in viewing a finely-detailed object, the observer gains no advantage from the object being closer than the far end of that range. The present author therefore defines an eye's near point as the visual distance which, if decreased, permits no finer resolution. This accords with the principle, described in the next Section, that the author has described as Threshold Resolution.

3.3 The Threshold Resolution principle

In measuring AoA, the Threshold Resolution principle is that the near point of an eye with its distance refractive error corrected is the furthest point from the eye at which it can see the smallest detail that it can see.

The principle has face validity for the measurement of AoA because it uses the concept of distinguishing the smallest detail, which is the main use of accommodation. It also has face validity because the visual resolution of the smallest detail requires the most accommodation. Threshold Resolution is a principle of measurement in other fields. Its general operation is discussed in Section 3.3.1.

No reports of the principle were found in the literature relating to AoA. It arose from the present author's observation, during a career in largely routine clinical practice, that to distinguish the smallest detail many individuals tend to immediately hold it about as close to their eyes as their accommodation may allow.

This led to a review (see Section 3.4) of the definition of AoA and to the development of a new instrument, described in Section 3.5, to measure it. The new instrument, the Threshold Resolution Unit (TRU) was designed, constructed, and prototyped in routine clinical practice by the present author prior to the inception of this research.

3.3.1 How the Threshold Resolution principle operates

The two test methods compared in this study operate on distinctly different principles. The RAF Rule uses blur-reporting while the TRU uses Threshold Resolution which is described as follows.

Threshold Resolution is a measurement paradigm that can improve precision in detecting certain signals such as identifying fine visual detail. A signal is a stimulus that can evoke a response in a specific receptor.

Signals have a certain number of parameters. Examples of single-parameter signals include the angular separation of two visible points of light, and change in air temperature. Two-parameter signals include squarewave energy, because this signal's only two parameters are its frequency and its intensity; pressure, which has parameters of force and area, and smell (molecular structure, intensity). Three-parameter signals include squarewave white flicker (the parameters are luminance, frequency and field subtense) and peripheral visual perception (contrast, subtense and eccentricity). Signals with several parameters could include combinations of the above, such as coloured flicker seen peripherally.

The parameters of any signal are either of magnitude or of type. In the above examples of different signals, frequency and molecular structure are examples of parameters that are of type. At least one parameter of any signal is of magnitude.

Threshold Resolution can improve assessment of the performance of a mechanism involved in resolving a signal that has more than one parameter. If the signal is held at the weakest level that can be resolved, adjusting any parameter of the signal will change the threshold value of all magnitude-parameters of the signal.

Visual functions are assessed with Threshold Resolution by adjusting one parameter to narrow another parameter's range of settings within which the signal can be detected. For example, to measure contrast sensitivity, suppose an observer tries to see many equidistant objects that are quite near to each other, too faint to see, and identical except differing in subtense. If their luminance-contrast is uniformly increased, the first to be resolved will be of a certain subtense and then, as that threshold of resolution is passed, a gradually increasing range of subtenses becomes visible. Similarly, when uniformly decreasing the subtense of visible objects of many contrast-values but otherwise identical, the number of objects visible will decrease until the object that is boldest disappears. Other visual functions that can be assessed by Threshold

Resolution include the perception of wide-field flash at a given wavelength (for which the magnitude-parameters are luminance and duration) and measurement of the monochromatic square-wave contrast-sensitivity function (subtense, contrast, and wavelength).

Westheimer (2016) elucidated the principle of assessing signal-detection performance by detecting the psychophysical threshold of the signal while adjusting a parameter of it. He described the adoption of this principle in clinical vision science as having occurred around seventy years ago.

In measuring AoA with the TRU, resolution of a high-contrast object depends on its height and its distance from the eye. Both of these parameters are of magnitude. Slowly reducing the object's height reduces the range of distances at which it can be resolved, until the minimum distance is pinpointed.

3.4 Definition of the amplitude of accommodation

AoA is important for seeing small objects. Therefore it could reasonably be defined with reference to smallness. The traditional and prevalent definition of AoA, such as that given by Millodot (2009) is based on “dioptric change” which is a means to an end but is not the end in itself. Accommodation is of value more because it enables visual resolution of small objects than because it enables the visual resolution of near objects. A definition based on smallness would also allow for possible change in visual acuity with accommodation.

In defining AoA, the concepts of smallness and of nearness are compatible, as follows. Suppose that an eye views the smallest object that it can resolve, where h is the height of the object and d is its distance from the corneal apex. Defining AoA through nearness, it is inversely proportional to d, whilst defining it through smallness it is inversely proportional to h, and d and h are proportionate to each other since the eye’s visual acuity at the near point can be taken as d/h as shown in Section 4.5.1. Therefore defining AoA through smallness allows for amplitude of accommodation to be expressed in dioptres.

Definition of AoA through smallness also excludes contamination by pseudoaccommodation, the depth of tolerance to blur. Pseudoaccommodation, defined by Sheppard *et al.* (2010) as functional near vision in distance-corrected presbyopic eyes, is not less than the eye’s depth of focus. It must be distinct from accommodation so that, for example, surgery to improve AoA can be adequately assessed (Glasser, 2008).

Any means of specifying accommodation is less precise if the eye cannot focus accurately. If the eye cannot focus well, due to static optical factors such as irregular corneal curvature or water-clefts in the lens, pseudoaccommodation can mask true accommodation. It does so through multifocality or pseudo-pinhole effects that reduce image quality although distance visual acuity may be acceptable. Multifocality and pupil-reduction (such as multiple pinhole spectacles) may be designed to help the presbyope through artificial extension of focussing but have not achieved widespread acceptance. The present author found no evidence, on searching the literature, that multifocal contact lenses are predominantly preferred by presbyopic wearers. Morgan *et al.* (2011) found that 29% of presbyopic wearers of contact lenses wore multifocal contact lenses. Neither have multifocal intraocular implants predominated in pseudophakes (de Silva *et al.,* 2016).

Considering all of the above, a suggested definition based on the Threshold Resolution Principle is as follows:

Amplitude of accommodation is the refractive error, measured at the corneal vertex, of a monofocal eye corrected for distance refractive error when it resolves the smallest object that it can.

3.5 Apparatus for the new method of measurement

For the new method, the Threshold Resolution Unit (TRU) was used. It is described below. In AoA measurement the TRU is alone in employing the Threshold Resolution principle introduced in Section 3.3.

The TRU is a hand-held light-box displaying a series of backlit objects in high contrast to their background, comprising thus a vision test-chart. It is shown in Figure 3.1a as approximately actual size, and is 12mm deep. The objects displayed were selected from the upper-case alphabet because upper-case letters:

- are more distinct
- embody optotype characteristics more than lower-case letters do, since upper-case letters include more straight and/or parallel lines
- and can present enough alternatives to sufficiently minimise false positive results due to guesswork.

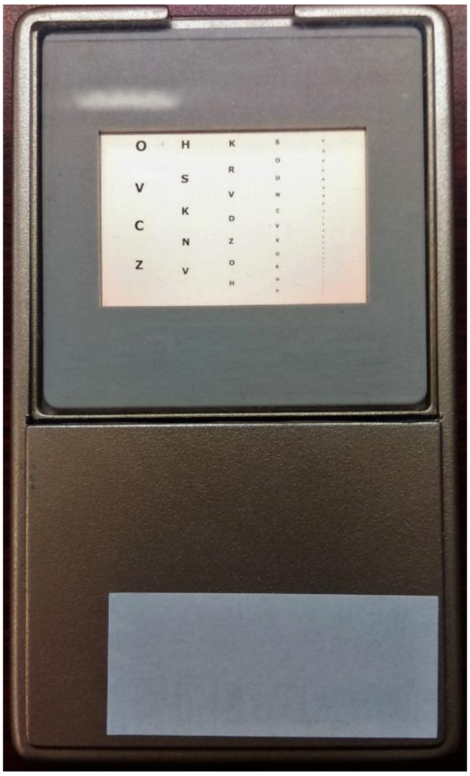


Figure 3.1a   Participants' view of the TRU, a new device for measuring amplitude of accommodation

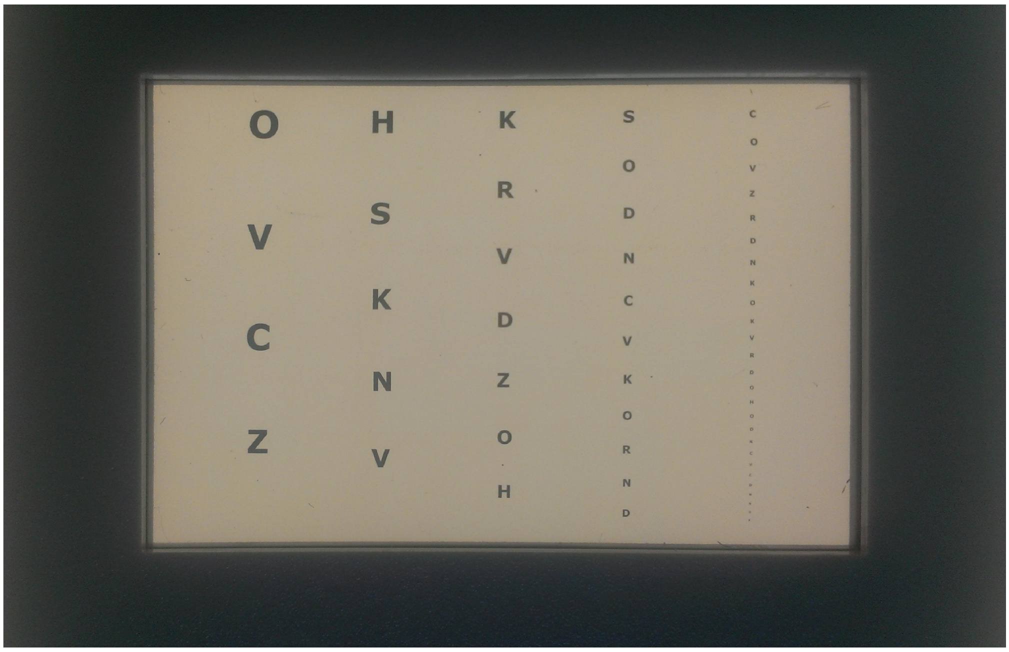


Figure 3.1b   Detail from Figure 3.1a: the panel of letters

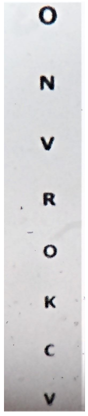


Figure 3.1c: the smallest letters displayed on a TRU, shown at x20

The mild vignetting at the lower end is an artefact.

In any font and size, individual letters differ in legibility for any person. So, a set of letters of similar legibility is used in vision test-charts. The two sets used most commonly are those recommended for this purpose by Sloan (1959) and in the relevant British Standard (BS 4274-1:2003). These both have ten letters that are the same except for C, K, O and S being in the Sloan set and E, F, P and U instead in the British Standard giving the latter a preponderance of long vertical lines so that uncorrected astigmatism may affect results. Therefore Sloan letters were used, to balance variety of form with similarity of legibility.

The font was selected as that which most closely resembled the commonplace British Standard 5x4 test-chart letter-format (which was not available in a medium allowing reliable production of a TRU transparency) . Test-chart letters are designed to present the smallest range of detection tasks, and thus a most precise endpoint, in measurement of visual acuity. Verdana Bold was the font most similar to British Standard 5x4 and was therefore selected. In fact the two fonts appeared identical except that in Verdana horizontal lines tended to be a little thinner than vertical lines, and that different letters' aspect ratios differed slightly, but those deviations would appear slight enough to be immaterial.

The letters were arrayed in order of height. Their height-order continued through the columns so that smaller letters formed columns to the right.

The height of each letter after the first was 95% of that of the letter above, balancing the requirements of precision of measurement with requirements of ease of use, as a smaller percentage would reduce measurement precision and a larger percentage would prolong testing and thus increase fatigue. The space between subsequent letters was 3.1 x the height of the letter above. This degree of regular proportionate spacing was chosen so that the range of letter-heights would be adequate in the space available without adjacent detail possibly influencing a letter's legibility, according to data reported by Leat *et al*. (1999).

Several arrays were produced, in white on black, differing in the order of the letters and the number of columns. They were printed in black on white and photographed using Agfa Ortho 25 Professional, a document-film giving negative transparencies with the finest grain and maximum contrast. Figure 3.1b shows a transparency, 36x24 mm in size as standard in photography, and Figure 3.1c shows a microscopic view of the smallest letters. Trials showed that five-column arrays as shown in Figure 3.2 were easiest to use, column centres being 6mm apart. This format was adopted for all experimental work.

The photography was scaled so that the largest letter on each transparency was 1.2 mm high, letter heights being checked with a measuring microscope measuring to 0.002mm. This maximum letter-height was chosen to be useful for low normal levels of visual acuity and accommodation found in routine clinical practice, such as visual acuity just above the standard for a UK Group 1 motor-vehicle driving license and able to accommodate to focus to a minimum of 45cm (ie AoA of about 2.25 D if no refractive error).

The smallest letter was 0.075mm high and one is shown at the foot of the column in Figure 3.1c. This size was selected on the basis that the letter would theoretically be just beyond the resolution ability of a patient with the best visual acuity levels and highest AoA found in routine clinical practice. The transparency displayed was quickly and easily changed so that participants did not memorise the letters.

Display luminance was even and maintained between 120 and 140 cd/m^2 because, according to Westheimer (1965) at that level visual acuity would be maximal and unaffected by moderate variations in luminance within, and moderately beyond, that range. Johnson (1976) established that the accommodative response was reduced at lower stimulus-background luminances.

Measurement with a spectrophotometer (Helios Alpha, www.spectronicdevices.com) showed that the radiance (which was from miniature, diffused, low voltage, tungsten-halogen lamps, the prevalent type of lamp for handheld backlit displays in widespread use at the inception of the TRU) was quite even across the visible spectrum and decreased slightly at shorter wavelengths (Figure 3.2). Such spectral distribution is commonplace for lighting equipment.

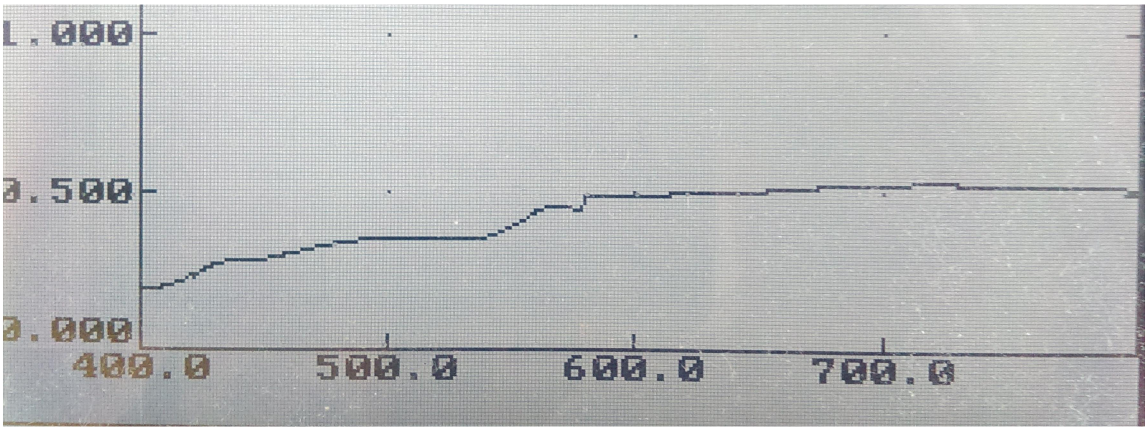


Figure 3.2 Spectrophotometry of the TRU (photograph of monitor of spectrophotometer)

In comparing AoA measurements with different methods, account may need to be taken of the possible effect of the target's spectral composition. Work by Aggarwala *et al.* (1995) showed that the accommodative response varied with extremes of spectral composition of the target. However, Atchison *et al.* (2004) found the effect to be negligible for slightly less extreme colours. The visible spectral output of the TRU is shown in Figure 3.2 as approximating to white. No evidence was found of any significant influence of wavelength on results using an apparently black-on-white target such as the TRU.

3.6 Apparatus for the reference method of measurement

The reference method of measurement used an autorefractor while the eye was accommodating to resolve a near target. The autorefractor selected for this work was the Grand Seiko WAM-5500 from Shigiya Machine Works Ltd, Fukuyama, Japan (Shigiya, 2017) pictured in Figure 3.3 from its marketing literature.

Figure 3.3   The Grand-Seiko WAM-5500 autorefractor

Factors supporting the selection of the WAM-5500 for this work included its following attributes:

- open-view design, permitting measurement of an eye looking at something else
- capability of recording measurements
- capability for a flow of rapid measurements
- small measurement-steps (0.01 D)
- ability to work with the particularly small pupils that occur (Marg and Morgan, 1949) in extreme accommodation
- the view of other researchers such as Kundart *et al.* (2011) who asserted that “the Grand Seiko WAM-5500 is now the gold standard for measuring transient accommodative effects” and Mallen *et al.* (2015) who stated that the instrument was pre-eminent in research into accommodation.

The instrument operates by projecting longwave light to be reflected from the fundus of the eye being measured, along its visual axis. Different authors give different wavelengths for this radiation, ranging from 720 nm to 950 nm, with most giving 850 nm. Such uncertainty would be surprising but authors' descriptions of some other aspects of the instrument's operation differ mildly, and Drew (2013) describing the instrument in particular detail remarked that "There is limited data on the operation principles of the WAM-5500". The value of 720 nm is from Win-Hall *et al.* (2010) and is probably correct because the radiation was visible in this research reported below, even to an observer with congenitally weak red-vision, and because Win-Hall *et al.*, unlike other authors, selected a narrow-pass filter to transmit the radiation.

The incident beam is from a ring object perpendicular to the visual axis so that the reflected beam forms an image of the object ring. The image is located within the autorefractor and its size and shape are related to the eye's refractive error. A detector within the instrument travels rapidly along the beam to locate the image when it is at the position of highest contrast. It then provides information related to the size and shape of the image and thus to the refractive error.

Radiation of 720nm is almost, but not quite, infra-red so the ring image projected was faintly visible to the participant. That could enable the participant to help to align measurement along the visual axis by moving laterally and/or vertically to place the fixation target centrally within the perceived projection of the ring. The participant could fixate visually at almost any distance and at a range of angles, with either or both eyes, through the instrument's semi-silvered mirror that reflects the radiation to and from the eye being measured.

Figure 3.4   Two views of the TRU mounted on the autorefractor

M = autorefractor mirror-housing

S = semisilvered mirror

R = rail from which autorefractor near-object hangs

T = TRU

A = adaptor for holding TRU

The TRU was mounted as the target on the autorefractor's near-vision target-rail using a custom-made adaptor shown in Figure 3.4. The adaptor's purpose was to offset the available range of target distance, compared to the range allowed by the instrument's own target-holder. This increased the upper limit of the measurement range of the WAM-5500 from 6.2D to 7.5D. Using the same instrument, Win-Hall *et al.* (2010) and Anderson and Stuebing (2014) reported measuring higher powers. That could be partly attributable to differences in the physical dimensions of adaptors. In this experiment, higher powers were measured by adding trial lenses as described in Section 4.4.2.1.

The rail's measurement graduations (which were not all accurate) were recalibrated to account for the position of the target as held by the adaptor. This recalibration was impeded by the instrument's delicate, oblique semi-silvered mirror and bulky frame through which the measurement beam was reflected to the eye, as it obstructed direct measurement of the distance from the eye to the target. The measurement from the eye to the mirror-housing was achieved, to an estimated accuracy of about ±2mm, by aligning a participant in measurement position at the machine and, using glass straight-edges, sighting the corneal vertex position relative to the housing and adding measurements of the housing and from the housing to the target.

The autorefractor was set to read mean sphere distance refractive error at the corneal apex. Its calibration for distance refraction was checked during each measurement session, using its own calibration attachment, to give a correction value for systematic error (although this was well below 0.1 D). A stream of measurements, occurring automatically at approximately five per second, was recorded as a .csv (Comma-Separated Variable) file on a Windows computer through the WCS-1 cable-connection software supplied with the autorefractor.

Results with the autorefractor have been empirically validated for distance vision (Sheppard and Davies, 2010b). To the extent described below, it also has some validation for measurement of AoA (notwithstanding that all autorefractors advertised for clinical use are designed to measure visual focussing primarily at distance rather than at near, if only because commercial refraction is principally for distance focussing).

For the validation, Win-Hall *et al.* (2010) measured 15 participants using a target providing from 2 D to 8 D of accommodative demand in 0.5 D steps. The following methodological factors in their investigation may, mildly but perhaps significantly, reduce the reliability of their results. They do not state whether measurements were made of the right, left or both eyes, or whether one eye was occluded; they give an uncertain size range of the visual objects that may have been coarse enough to be resolved at beyond a metre so a significant degree of unsystematic error due to depth of focus as described by Rosenfield and Cohen (1995) and Atchison *et al* (1997) may have been present and the target appears to have been positioned on the midline which would have caused systematic error as shown in point 15 of Section 2.4.4; while the instrument, which can provide measurements in steps of 0.01 D, was set to measure in 0.25 D steps, which would have reduced precision.

Notwithstanding the foregoing, they found responses of around three-quarters of the stimulus level and that this apparent disparity between stimulus and response increased mildly with increasing accommodation. Some of that disparity may have been due to depth of focus as mentioned above, and that contention may be supported by the disparity's substantial variation between participants. At levels above 5.5 D the disparity increased substantially, perhaps reflecting that the amplitudes of accommodation of some participants were lower than may have been assumed. This contention is supported by measurements showing near-parity between stimulus and response in the same investigation with trial lenses replacing accommodation, and also measuring a model eye. Win-Hall *et al*. did not finally endorse the WAM-5500 as accurate for measuring accommodation.

The smaller study by Kundart *et al.* (2011) used nine participants' right eyes and a slightly coarser target (N12 print). The response to stimuli of two, two and a half, three and four dioptres was found to be about 75% (similar results were obtained viewing N9 print on a different display for ninety seconds) similar to that obtained by Win-Hall *et al.* given above.

Aldaba *et al.* (2017) measured accommodation for 28 participants with the WAM-5500 but did not set out to validate it. They obtained responses lagging over 20% behind the stimulus, which may have been partly due to the low content of fine detail in the visual object. an effect described by Rosenfield and Cohen (1995).

3.7 Experimental aims and design

The hypothesis in Section 1.5 was examined empirically, using the following methodology. Repeatability and reproducibility of the prevalent method and of a novel method of measuring AoA were examined and compared, by randomised crossover comparison of repeated measures. The trueness of both methods was assessed by comparing each method's results with those of a reference method.

The new method used the TRU described in Section 3.5, the prevalent method of measurement used the RAF Rule introduced in Section 1.4 with the push-up technique described in Section 2.3.2.1, and the reference method used the Grand Seiko WAM-5500 introduced in Section 3.6.

The TRU's repeatability was assessed in greater depth, by repeated measures in which trial lenses were worn to provide double-masked adjustment in the result of each measurement. The value of taking measurements of AoA using an alternative technique with the TRU was explored.

Throughout this experiment, the term AoA is not a determination of the true degree of accommodation that an eye can exert, because participants' refractive error was not added to the measurement. Absolute determination of AoA requires correction for refractive error, as described in Section 2.4.3.3. Uncorrected myopia, a common type of refractive error described in Section 1.2.2.2, would increase the measurement, uncorrected hypermetropia (Section 1.2.2.1) would reduce it, and uncorrected astigmatism (Section 1.2.2.3) would reduce the precision of the measurement. However, to achieve the aims of this experiment given above, measurement of participants' refractive error was not required because the methodology was to compare measurements with different methods. For the same reason, it would not be necessary to exclude participants with health conditions such as diabetes that may affect AoA.

Measurements were made monocularly, with monocular viewing. This was a frequently reported mode in research involving AoA measurement, so selection of this mode facilitated comparison with the results of such research, and would be the method of choice in clinical work where interocular difference may be of interest. It was also the mode advocated in the clinical textbooks mentioned in Table 2.3. Binocular stimulation would be likely to produce slightly different results due to factors described in Sections 2.4.3.2 and 2.4.6.

Variation in the results of measurement is due to measurement imprecision plus any change in the quantity being measured. It is not known whether AoA is constant. It may vary significantly in the minutes or even seconds between successive measurements. Therefore this study planned measurement with one method providing two simultaneous data streams; the height of the smallest letter resolved, and its distance from the eye when resolved. It also set out to assess the TRU's range of letter-height.

Three contrasting methods of measuring AoA, and the background to their use, have now been introduced. In the following chapters, comparison of results with them is described and discussed.

Chapter 4 Method of investigation

This Chapter describes the experimental methods used in the research. The Chapter starts with an overview of the path or procedure, below and im Figure 4.1, and then describes the participants, the assessment of reliability, the procedure in more detail, and the approach to data analysis.

In the first session of the experiment (Session 1) initial readings were taken with the test methods (the RAF Rule and the TRU). Then other TRU readings with fixed adjustments to measurement conditions were made, to assess the method's robustness. The initial readings were then repeated to conclude the session, to assess repeatability.

In the second session of trhe experiment (Session 2) more readings with the test methods were taken, to assess reproducibility between sessions and between investigators. Also in Session 2, comparison was made between results with the test methods and results with the reference method.

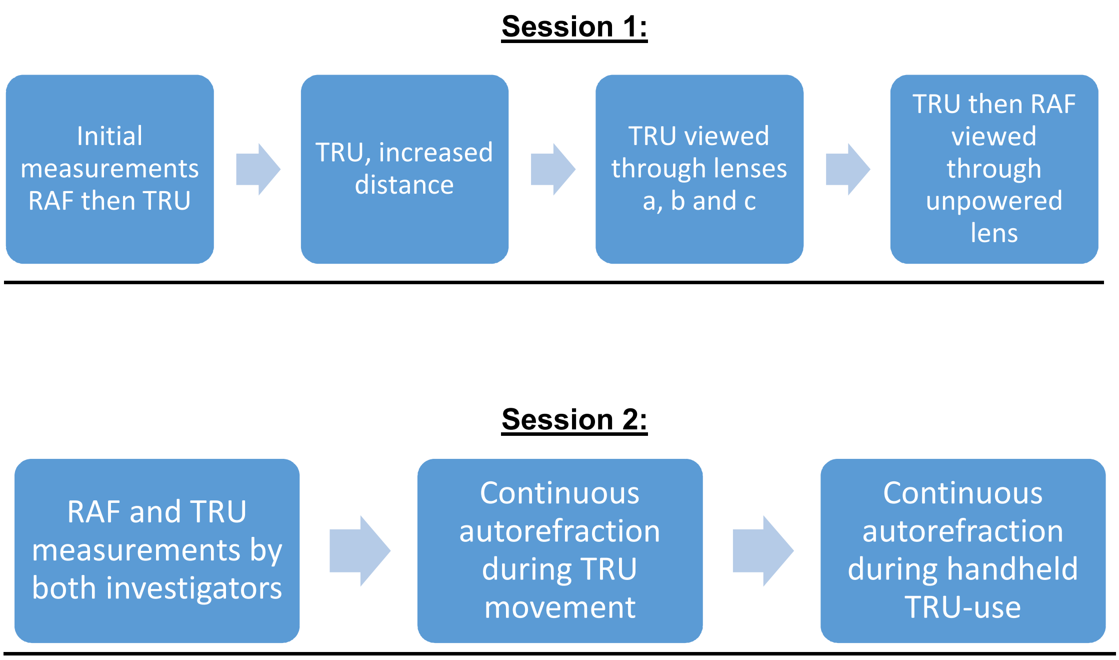


Figure 4.1 Overview of measurement process

The research adhered to the tenets of the Declaration of Helsinki. Appendix 3 shows approvals obtained for the research from academic bodies. Approval was first granted by the Research and Ethics Committee of London South Bank University, then by the Institute of Optometry, and then by the IRAS system in the NHS for reasons given in Section 4.1.1.

4.1 Participants

Participant selection was based on the following inclusion criteria:

- familiar with the English alphabet
- basic use of spoken English
- age from 18 to 43 years inclusive
- right eye optically clear and undistorted, as shown by retinoscopy, a technique described in Section 2.3.1.2
- right eye refractive error below 3.00 D, of myopia or hypermetropia, in any meridian and less than 1.50 D between meridians, as assessed by retinoscopy
- interocular difference below 1.50 D in refractive error (accounting for spherical and astigmatic corrections by adding half of the astigmatic correction to that of the myopia or hypermetropia) as assessed by retinoscopy
- right eye could read five-point print at 50cm through the habitual single-vision distance refractive correction if used
- left eye visual acuity exceeded 6/6 (the specified minimum for the binocular visual acuity of commercial pilots registered in the UK) with the habitual single-vision distance refractive correction if used

Data were recorded from only one eye of each participant, as explained in Section 2.2.

4.1.1 Recruitment

Recruitment was by publicity material, shown in Appendix 4, in the district around the principal investigator's practice and (Appendix 5) from the practice for its patients who fitted the participant criteria shown above. Enquirers aged 18 to 43 were given an information sheet (Appendix 6) and consent form (Appendix 7) and were invited to discuss participation.

Although an incentive was included (a prize draw mentioned in Appendices 4, 5 and 6, for which the prizes were provided by the author) recruitment was too slow so both recruitment and the research overall were then extended to include a large NHS workplace familiar to the author. This required the approval of the hospital's Research and Development Committee through the IRAS system. The IRAS approval is included in Appendix 3.

Participants' paths are shown in Figure 4.2.

Response of interest to poster in window of practice
and/or
Response of interest to letter to patient of the practice

↓

Discussion between applicant and practice staff

↓

Appointment made for Session 1

↓

Assessment of suitability, leaving study if any inclusion criterion unmet, and Consent

↓

Session 1, ending with arranging appointment for Session 2

↓ **preferably a week after the first session**

↓ ↓

↓ **If appointment not kept, three (max) rebookings**

↓ ↓

If appointment kept, Session 2 with conclusion of participation ← **appointment kept** / **no appointment kept for Session 2**

↓ ↓

Participants who completed both sessions of the experiment	Participants who completed only Session 1

Figure 4.2 Participant actions

4.1.2 Sample size calculation

Sample size estimation was not guided by previous research, because there was no method of known trueness or precision against which to compare an experimental method, and because no published reports were found of the possible variation of an individual's AoA over the timescales that this research covered. However, data were available from the first 33 participants' results prior to calculating the required sample size. The data were suitable for sample-size calculation, according to criteria given by Bland (2010) as follows. The means of the five TRU measurements per participant were normally distributed ($p = 0.55$ by the Shapiro-Wilk test) and showed insignificant correlation (Pearson correlation coefficient r of 0.091) with CV (defined in Section 4.2). Similarly, a scatterplot of TRU measurement-variance against mean measurement, for each of these 33 participants, showed that the variance appeared unaffected by AoA.

Therefore a sample-size calculation was performed, using the method described (for a repeatability study) by Bland (2010) with this dataset. The sample-size calculation was to estimate how many participants would be required to establish the repeatability of the TRU to an adequate degree. It was not done for method-comparison outcomes, since relevant aspects of accuracy of the comparison methods in this study had not been assessed.

The sample-size calculation was based on the five measurements per participant , a 95% confidence interval for the population within-subject standard deviation, and ±6% was selected as a level of precision that would yield useful results. It was assumed that each participant's AoA would be constant during the measurement session. The calculation showed that measuring at least 134 participants would give adequate confidence.

4.2 Clarification and definition of reliability of measurement

In this study, the six terms listed as i. to vi. below will be used to describe the various attributes of a measurement method's reliability. They are based on definitions given by the International Organization for Standardization (1994) for specifying measurement accuracy. For all of these attributes, lower values represent better methods.

i. Accuracy: how close a single measurement is to the true value of the item or function being measured. It is affected by trueness and precision, both defined below.

ii. Trueness: how close the mean of many repeated measurements of the same item or function is to the true value of the item or function being measured, ignoring the additional effect of precision which is defined below. Measurement is with the same method by the same investigator under the same conditions and in the same experimental session.

iii. Precision: the effects of reproducibility and repeatability, both defined below.

iv. Reproducibility between investigators: the closeness (to each other) of measurements of the same or identical item or function, with the same method, under the same conditions and in the same experimental session, but by different investigators.

v. Reproducibility between sessions: the closeness (to each other) of measurements of the same or identical item or function, with the same method, under the same conditions and by the same investigator but in different experimental sessions.

vi. Repeatability: the closeness (to each other) of measurements of the same or identical item or function, with the same method by the same investigator under the same conditions and in the same experimental session.

Repeatability can be expressed as a Coefficient of Variation or CV, calculated as the standard deviation of repeated measures divided by their mean (Armstrong *et al*., 2011) though it should be noted that in calculating the CV, if the mean (the denominator) is negative, its minus sign should be omitted. However the CV may not be the best index for comparing the repeatability of methods, particularly where, as in this study, small and differing numbers of repeated measurements are taken with the different methods. Therefore in this study the CVs between every two measurements were averaged for each participant, giving an expression termed Mean Pair Variation (MPV). MPV, like CV, is expressed as a proportion, unlike confidence limits which give an absolute value.

In trials with test data the MPV appeared likely to represent repeatability better than the CV, perhaps because the MPV would make more use than the CV of the data, This arises because the number of unique comparisons between measurements is greater for the MPV than for the CV (if there are more than three measurements per participant).

The International Organization for Standardization (1994) stated that repeatability described the variation between repeated measurements of identical test items. However, in biometric measurement inter-individual variation of the degree of variation can be expected in addition to intra-individual variation, because the repeatability of a measurement method may vary between individuals measured by it. No widely-accepted biostatistical formula for repeatability of methods of measuring human performance was found on searching the literature. For this study, a formula was taken for the 95% confidence limits of a biometric method (in this case, of measuring AoA) based on recommendations by Fraser and Fogarty (1989) and the International Organization for Standardization (1994). If the mean of all participants' MPVs is M and the standard deviation of all participants' MPVs is S, the formula gave a value termed, in this study, the Biometric Mean Pair Variation for 95% Confidence Limits, or BMPV(95%) where:

$$BMPV(95\%) = +/- 1.385\sqrt{(M^2 + S^2)}$$

BMPV(95%) would appear to offer a valid index by which the repeatability of biometric methods can be reliably compared.

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4.2.1 Preliminary investigation, to explore the repeatability of measurement of the distance from the TRU to the eye

In this Section prior work is described exploring the repeatability of techniques contributing to measurement with the TRU (as it was used as in the main experiment as described in Section 4.4.1.2).

TRU measurement involves measuring the distance between two points, the smallest TRU letter read and the corneal vertex. It could not involve physical contact with the TRU as that might alter the distance being measured. This measurement would ideally have used a validated, safe and unobtrusive tool. However, the eye is too sensitive to allow the application of any current distance-measurement technology that might be feasible for clinical use.

Measurement was therefore made without touching the eye or the TRU. It was from a plane containing the corneal vertex to another plane, parallel to the first, containing the letter, and the measurement was taken parallel to the line containing those two points.

This allowed measurement by using a commonplace steel rule. Other possible methods of greater technological sophistication were considered but did not show an adequate improvement in accuracy to set against the limitations imposed by each particular method.

The repeatability of such measurement would depend on the investigator's skill in avoiding parallax errors, including visual assessment of the planes being parallel and perpendicular to the rule held as close to the two points as possible without distracting the participant. This repeatability was assessed empirically as follows. Five masked rules, shown in Figure 4.3, were produced. Each rule bore equidistant coded graduations of an unknown, differing, close proportion of a centimetre. This masking was to avoid the possible influence of operator bias. There were seven participants, specified as in Section 4.1. None of the participants had any previous knowledge of the TRU. The principal investigator asked the participant to hold the TRU steadily (without reading it) in an unset position typical of measurement, and measured the distance from the corneal vertex to the TRU letters with each of the five masked rules.

Six measurements were taken for each participant, one with each rule selected in random order and then again with the first rule selected. All measurements for each participant were completed in less than two minutes. After the measurements were completed they were decoded to millimetre measurements.

Figure 4.3 Masked rules

The data are analysed in Appendix 8 and summarised here. Data from each participant were normally distributed (Shapiro-Wilk test, $p > 0.7$). They showed that measurement with a rule, as described in Section 4.4.1.2 for this research, had a BMPV(95%) of ±1.93%. This was felt to be an acceptable level of repeatability for the distance-measurement technique used for the TRU in this study.

However, this validation of this technique of measurement was limited because it did not address reproducibility, involved a small number of participants, and covered a limited measurement range (measurement error would probably be proportionately larger at higher levels of AoA and less at lower levels).

4.2.2 Preliminary investigations, to explore the repeatability of visual acuity measurement using the TRU

Biological systems' performance may normally vary over any timescale. The sensitivity of a biological system that registers a stimulus may show such inherent variation. Therefore there is a range of stimulus levels at which the stimulus is sometimes but not always detected. A visual object in constant conditions, configured to be near to an individual's threshold of resolution, will sometimes be identified by an individual who will fail to identify it at other presentations. A relevant example of this range of uncertainty of resolution at threshold would be the repeatability of visual acuity measurement as discussed by Lam *et al.* (2008). This uncertainty occurs in TRU use as it involves identifying fine detail.

To evaluate this source of variation, a pilot assessment of TRU legibility was carried out. This was to find the range of letter-height within which a letter on the TRU was correctly identified at between 5% and 95% of presentations. There appeared to be no publication reporting sufficiently relevant findings. Fifteen participants specified as in Section 4.1 were asked to read five TRUs matched for luminance contrast at a fixed viewing distance of approximately one metre, from the largest letter to the smallest possible. Measurement took about two minutes for each participant. The number of letters that each participant read on each TRU was recorded. It was also recorded for fourteen different but similarly specified participants holding the TRU at the near point, where most letters could be resolved.

4.3 Procedure of the experiment

This is summarised in Figure 4.1. Experimental work took place in a room with suitable lighting, space, comfort, quiet, privacy, and reception facilities. Participants, seated comfortably, wore their single-vision distance refractive correction (spectacles or contact lenses, obtained outside this study, if any) if habitually worn for at least some viewing beyond arm's length. These were of powers below 3.00 D as shown in Section 4.1. A trial frame was worn, containing the right eye refractive correction if required as above, and the left eye was occluded.

All measurements used standardised procedures and instructions, given below. They were made with the RAF Rule, the TRU and the autorefractor, in the order shown in Table 4.1 wherein

T = distance from the participant's right corneal apex to the smallest TRU letter read, in millimetres
P = position in the TRU's series of letters of the smallest letter (of height H) read
R = RAF Rule measurement of near point distance, in millimetres
A = autorefractor measurement of ocular refraction, in dioptres.

All measurements were made by the principal investigator except for those in Condition 6 in Table 4.1.

Table 4.1 Principal outcome data in each measurement condition

	Condition	**Outcome Data**		
		Session 1:		
1	Initial	T1	P1	R1
2	TRU held further	T2 (preset)	P2	
3	TRU, lenses a, b, c & u added	T3 a, b, c & u	P3 a, b, c & u	
4	Repeat with RAF Rule			R4
		Session 2:		
5	Revisit	T5		R5
6	Secondary investigator	T6		R6
	Objective automated measurement		A1, A2, A3, Ah	

4.3.1 First measurement session

Inclusion criteria given above were checked and the consent form completed. For adequate anonymisation the participant's details were listed on a password-protected Excel spreadsheet in which each participant was allocated an individual sequential number (ISN). Outcome data were recorded with their ISN on a separate password-protected Excel spreadsheet.

On their completing this session, participants were asked to return at an agreed appointment for the remaining session. Participants' results were not viewed between the conclusion of this session and that of the remaining session described in Section 4.4.2 below.

4.3.1.1 Method with the RAF Rule

Each participant's AoA was measured with the RAF Rule used as per established practice (eg Barrett and Elliott, 2003) at the start and end of the session as follows. The investigator positioned the RAF Rule, setting its target print (the line labelled N5) well beyond the participant's likely near point. This was the smallest print on the RAF Rule that was printed legibly as the edges of the characters were imprecise as shown in Figure 1.4, although one other face of the slider included smaller print.

Ambient lighting was arranged, and checked with a suitable luminance-meter. This was to maintain the test object's luminance, within its range of travel, between 80 and 120 cd/m^2 as specified by the International Council of Ophthalmology (1988).

The investigator directed the participant's attention to the target print, giving standardised instructions as outlined in Barrett and Elliott (2003) for the push-up method. Instructions were given from a printed script including "Keep looking carefully at these letters to keep them clear and tell me when they just start to get blurry" while starting to slowly move the slide towards the participant. The speed of movement was approximately 0.5 dioptres/second as in Evans *et al.* (1994).

When blur was reported the slide was immediately stopped and the participant encouraged to refocus the letters to make them clear again. If the participant reported that sharpness was restored, the slide's approach was resumed until the participant reported being just unable to prevent the print from just starting to get blurry whereupon movement was stopped and the target's position on the rail was recorded as R1 and the movement was not restarted. A further reading R4 was taken in the same way at the end of the session.

4.3.1.2 Method with the TRU

Instructions for participants using the TRU, given when handing the device to the participant, were “Please hold this as close to your eyes as you like, to read the letters down the far right-hand column”. If the participant hesitated, the examiner added “OK, start with the column next to it”. When the participant reported being unable to read a smaller letter the investigator moved the TRU a little nearer, then a little further away, and then said “OK, now put it up where it’s best to see the small letters”. Certain incorrect responses were accepted as shown here:

Letter	Incorrect response accepted
C	G
D	O
H	N
K	X
N	H
O	Q
S	B
V	Y

The participant was encouraged to continue until two letters adjacent in the series were incorrectly read. Then the participant was asked to stay very still and the measurements for Condition 1 (see Table 4.1) were recorded. These were the value P1, and the distance T1 which was measured with a steel rule taking care to minimise parallax.

The TRU's letter chart was changed for each successive measurement, to avoid any possible influence of memory by the participant.

Following the above readings of T1 and P1, the TRU was repositioned one-sixth (16.67%) further from the eye for the pre-set measurement T2 where the value of P2 was then taken. By similar triangles, the visual angle subtended at T1 by P1 would theoretically be that subtended at T2 by (P1 - 3.16).

A trial lens was then placed in a trial frame, or clipped to the front of spectacles if worn, in front of the participant’s right eye. This lens was selected at random, using a random-number table, from a set of thirty trial lenses all differing in power and differentiated only by a code number.

The lenses' powers, measured with an electronic focimeter to a precision of ± 0.01D, were quite evenly spread from -1.24D to +1.29D and masked from the investigator. This range of powers caused levels of spectacle magnification that were not large enough to be taken into account (being less than half of the difference between the sizes of adjacent letters in the TRU series) so values of P would have been affected very little by magnification due to the power of the trial lens.

Readings of T and P were repeated as initially made but viewing the TRU through the additional lens. They were repeated with two other lenses similarly selected from the same masked set and then with a plano lens, giving readings T3a, T3b, T3c, T3u, P3a, P3b, P3c and P3u.

There was at least twenty seconds' break between measurements with the TRU. Participants were told that they could have additional rest periods if they found the task tiring, and none accepted that offer.

4.3.2 Second measurement session

This was the same as the previous session except as follows. Measurements were taken by the principal investigator and a secondary investigator, an optician who had received written instructions shown in Appendix 10 for the TRU and had practised using it under the principal investigator's supervision but whose routine clinical duties did not normally include the measurement of AoA. Participants were measured as before in the following four ways:

1) with the TRU by the principal investigator
2) with the RAF Rule by the principal investigator
3) with the TRU by the secondary investigator
4) and with the RAF Rule by the secondary investigator.

Each participant thus provided four measurements and the two investigators were masked as to each other's measurements. Four events can occur in 24 possible different orders. To reduce possible order effects, the 24 possible orders of measurement were randomised to participants using a Latin Square design.

4.3.2.1 Method with the autorefractor

To allow for possible slight variation in autorefractor measurements its calibration was checked using the model eye supplied with the autorefractor just before each participant arrived. The participant was then seated comfortably at the autorefractor with the same refractive correction, if any, worn for Session 1, and the left eye occluded. The TRU was positioned as the fixation target on the autorefractor as shown in Figure 3.4, approximately 25% further than the mean of the previous measurements of T made in Sessiom 1 as shown in Table 4.1. Where those measurements suggested a high enough AoA, the participant viewed the TRU through just enough added negative lens power to ensure that the near point would fall within the autorefractor's measurement range. This added power, adjusted for effectivity at the corneal vertex, was subtracted from all accommodation readings made through it.

The examiner then instructed the participant as follows. "Please stay very still and do not speak. When I switch the screen on please find the tiniest letter on it that you can read, noting which column it’s in and the letter above it. Keep trying to read the very smallest letter that you can as I bring it a little nearer. If you see a faint flashing red circle, ignore it – it's just part of how the measurements are made".

Commencing recording refraction with the autorefractor, the examiner then brought the TRU slowly and smoothly along the rail towards the participant while continuing to instruct the participant to mentally note and continuously revise the smallest TRU letter discernible. The TRU was moved nearer to the eye at a speed of approximately 5% of the eye's distance per second until well within the near point, with the operator maintaining alignment of the instrument's measurement beam with the participant's visual axis.

After each recording, the measurements were downloaded for subsequent storage and analysis by Microsoft Excel as .csv files, and the TRU letters were changed. The procedure was repeated, attempting to provide three recordings of the eye’s refraction changing. The procedure was then repeated again while the participant held the TRU and adjusted its position to be able to read its smallest letters possible. To maintain alignment of the measuring beam with the visual axis during this measurement, the operator guided the participant by observing the eye position on the autorefractor screen. Finally, calibration was rechecked with the model eye as above, participants' questions were invited and answered, and then participants were discharged from the project with thanks for their participation. .

4.4 Data Analysis

4.4.1 Initial preparation of data

All values of T and R were converted to dioptric values.

Values of P were converted to H, the letter height in millimetres, by this formula:

$$H = 1.2 \times 0.95^{(P-1)}.$$

For each participant, the following mean values were calculated:

Rm1, mean of R1 and R4

Rm2, mean of R5 and R6

Tm1, mean of T1, T3a, T3b, T3c and T3u

Tm2, mean of T5 and T6

As AoA decreases gradually through life, account was taken of the small loss likely from Session 1 to Session 2. The values of the adjustments made, shown in Table 4.2, were according to data from objective measurements of AoA by Anderson *et al.* (2008) and Leon *et al.* (2016) since these two studies were largely objective and more recent than most and, although their methods were different, their results agreed relatively well with each other (and with comparable measurements in this study).

Table 4.2 Loss of accommodation likely, due to age between sessions

Age	Probable AoA	Hence annual loss in each of next five years
years	D	D
15	7.00	0.028
20	6.86	0.074
25	6.49	0.166
30	5.66	0.294
35	4.19	0.352
40	2.43	0.260
45	1.13	

VA measurements were obtained as follows. Since VA is the smallest angular detail that the eye can resolve, it can be expressed as a cotangent and it is then a measure of smallness. Smallness was proposed in Section 3.4 as a basis for defining AoA. Expressed as a cotangent, smallness may also be useful as a basis for expressing VA. It provides a relatively clear, simple, rational (i.e. proportionate to resolving power) and convenient index, compared to other means of expressing VA prevalent in current clinical and research use such as Snellen and LogMAR. In the common six-metre Snellen visual acuity test chart, the largest letter (87.3mm in height) is termed 6/60 which would be 69 if expressed as a cotangent. Some charts have letters small enough to measure the highest levels of visual acuity commonly encountered such as 6/3 which would be 1376 as a cotangent.

With appropriate small-angle approximation, this is the distance of the detail from the eye divided by the size (or "height") of the detail. Where measurement with the TRU provided values for H and T, these data were used to calculate VA. At the near point the VA was termed VN.

4.4.2 Statistical analysis

For method-comparison, Bland-Altman difference plotting (Bland and Altman, 1986) was used. It has been advocated by authors including Zadnik *et al*. (1994) and McAlinden *et al.* (2011). T-tests were also used to compare paired mean results.

Statistical testing was carried out with Microsoft Excel 2013 including its Data Analysis add-on, after tests of normality were carried out with SPSS version 21 (IBM Corporation). The tests of normality used were the Kolmogorov-Smirnov test and the Shapiro-Wilk test. Razali and Wah (2011) validated both tests, finding that the Shapiro-Wilk test was the most powerful and that all testing for normality is more reliable with larger sample sizes. They recommended using the Shapiro-Wilk test for series smaller than fifty items of data.

Grubbs' test, a statistical test used to detect outliers in a univariate data set assumed to come from a normally distributed population, was used (as recommended by International Organization for Standardization (1994)) at www.graphpad.com. Statistical tests (t-test, z-test and ANOVA) comparing means or medians were two-tailed. Statistical analyses took a p value of <0.05 as statistically significant.

4.4.3 Principal outcomes

The investigation described in this Chapter was to obtain, record and analyse data towards the purpose given in Section 1. The data were analysed as follows, so that their significance for clinical practice could then be assessed.

Bland-Altman difference plots were used to compare:

- agreement and bias between the new and the prevalent method, ie Tm1 vs Rm1
- precision of those methods by comparing the agreement between results for:
  - repeatability, ie T1 vs T3u, T1, T3a, T3b, T3c and T3u, and R1 vs R4
  - reproducibility between sessions, ieTm1 vs T5, and Rm1 vs R5, and
  - reproducibility between investigators, ie T5 vs T6, and R5 vs R6
- agreement and bias between the new method and objective measurement, ie Tm2 vs A
- agreement and bias between the prevalent method and objective measurement, ie Rm2 vs A.

The possible influence of extreme accommodation on visual acuity was investigated through analysis of visual acuity data using the TRU as shown in Section 4.5.1. This was to determine whether acuity measurement might contribute to evaluation of TRU repeatability if the TRU were found to be accurate.

In selecting a method of measuring AoA, the clinician would probably find it more useful to know the accuracy of methods in proportionate rather than in absolute terms, giving a margin of error proportional to the AoA. However, in clinical work, the 95% Confidence Limits might be more useful. Therefore both of these indices, proportionate and absolute, are reported.

4.5 Conclusion of chapter

This chapter has summarised the experimental methods in this research. The participant selection criteria and sample size calculation have been outlined. This was followed by consideration of the definition of reliability, and a description of the experimental procedure, methods of data analysis, statistical analysis, and principal outcomes.

Chapter 5 Results

This chapter includes the results of the comparison of measurements made with the three methods for all 144 participants.

5.1 Congruence of participant data

143 of the participants provided measurements in Session 1. Due to an administrative oversight, first session measurements were missing for the other participant. Of the 144, 111 participants undertook Session 2 and provided measurements. The other 33 either went out of contact or failed to keep any of a maximum of three consensually-booked appointments to return for Session 2.

The ages and genders of the 144 participants are shown in Figure 5.1. 44% of participants were male, participants' mean age was 30 years (SD 6.8 years) and participants' age-distribution correlated well (Pearson r = 0.99) with a hypothetical perfectly even age-distribution. These findings were true for each gender in each experimental session.

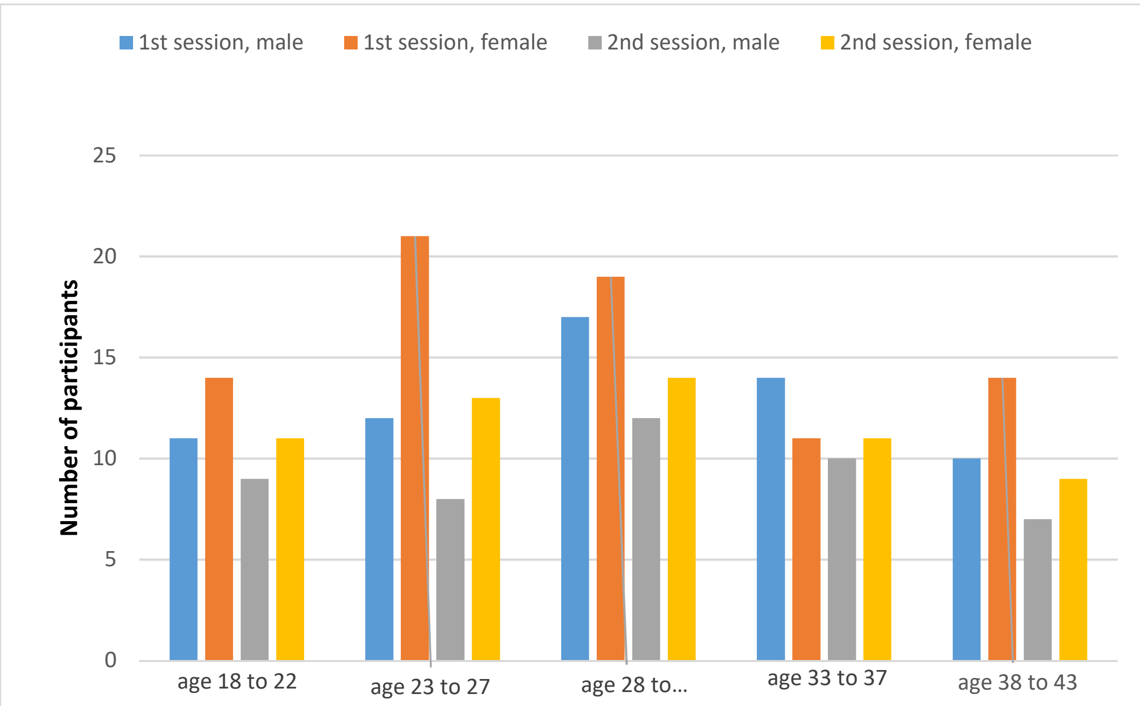

Figure 5.1: Participant numbers in each experimental session by age in that session and by gender (totals: 144 in Session 1, 111 in Session 2)

The average number of days between sessions was 85. The range was 3 to 339, the median was 10 and the interquartile range was 115.75 days.

45% of the participants who failed to return for Session 2 were male, as for those who did return. The ages of participants in these two groups differed little (mean 30.4, median 30.7 for those who did return and mean 30.9, median 31.3 for those who did not) and this was confirmed by a z-test comparing the median age of participants in one group with that of the other group ($p = 0.72$).

One difference was noted between participants who returned for Session 2 and those who did not. It was that participants who returned had higher AoA by both methods of measurement (TRU 14.7% higher, RAF Rule 14.5% higher). z-tests for these nonparametric series showed that the group medians differed but with only weak statistical significance ($p = 0.10$ for the TRU and for the RAF Rule). The difference could suggest simply that participants who did not complete the experiment tended to be moderately more hypermetropic (about 0.75D) than those who did. Participants' refractive error was not determined accurately enough to assess this possibility.

All 111 participants in Session 2 provided measurements with both the RAF Rule and the TRU for two investigators. However, the autorefractor sometimes failed to provide readings. The extent to which this failure occurred is shown in Figure 5.2. The groups shown in Figure 5.2 were of similarly balanced age and gender. Figure 5.2 shows that 72 participants, which was only half of the number of participants enrolled, provided all four autorefractor measurements, and 93 provided all but the handheld measurement.

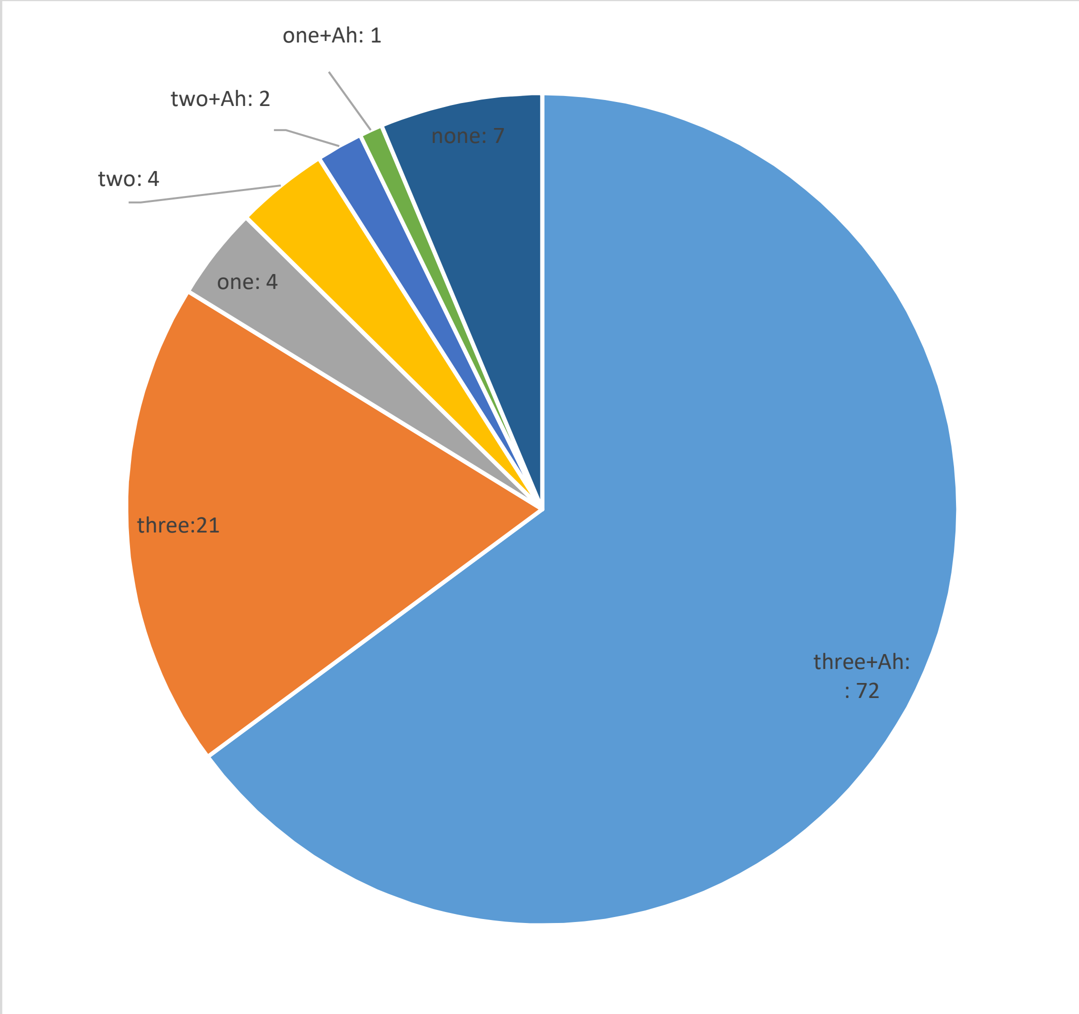

Figure 5.2 Autorefractor measurements per participant n = 111

Ah = handheld TRU

Success in obtaining autorefractor measurements appeared to be linked to the TRU result for AoA. With the target on the autorefractor rail, the 18 participants who gave fewer than three readings showed higher mean AoA than the 93 participants for whom the autorefractor obtained three readings (10% higher by the RAF Rule and 11% by the TRU) whereas the eleven participants for whom the autorefractor provided one or two of the three measurements had autorefractor results only 3% higher than the rest. Z-testing showed a significant difference between the medians for the TRU but not for the RAF Rule.

This inconsistency of autorefractor function may be of interest in considering autorefractor reliability at high levels of accommodation. Pupil diameter was simultaneously recorded by the autorefractor and did not appear to relate to success in obtaining measurements but this possibility was not systematically analysed.

5.1.1 Normality of results' distribution

In comparing methods of measurement, Bland-Altman difference plotting (Bland and Altman, 1986) has been widely used to investigate how closely the results of one method agree with the results of another method. Bland-Altman difference plots are more reliable if the differences between the two methods approximate a normal distribution (Bland and Altman 1999). In this research project all of the data-series of AoA measurement were paired. The differences between pairs of series were first analysed to determine whether each of the twelve difference-series had a 95% or greater probability of matching a normal distribution, before being analysed by Bland-Altman difference plotting to investigate method-agreement. The analysis showed that most of the series of difference were normally distributed.

There were some minor departures from normality of distribution. Five of the twelve difference-series were not normally-distributed, according to the Kolmogorov-Smirnov test ($p < 0.05$). One of these satisfied the Shapiro-Wilk test for normality ($p = 0.158$) which, as shown by Razali and Wah (2011) generally detects lesser departures from normality than the Kolmogorov-Smirnov test does (as was the case with most data series examined with both tests in this research). The remaining four non-normal series were:

(1) The differences between mean TRU and mean RAF measurements in Session 1 (Kolmogorov-Smirnov test, $p = 0.005$)

(2) The differences between TRU measurements in Session 2 (Kolmogorov-Smirnov test, $p = 0.031$)

(3) The differences between the first and last TRU measurements in Session 1 (Kolmogorov-Smirnov test, $p = 0.019$) and

(4) The differences between RAF measurements in Session 1 (Kolmogorov-Smirnov test, $p = 0.001$).

However, the following considerations support assessment of the data in this study by parametric methods. Outliers were selected according to Grubbs' test and additionally if more than three SD from the mean. They were all in the more populous of the two tails, and formed a negligible proportion of the data. Series (2) in the list above became normally distributed by the Shapiro-Wilk test ($p = 0.072$) when just the most extreme outlier was removed, (1) and (3) became normally distributed by the Kolmogorov-Smirnov test ($p = 0.059$ and 0.064 respectively) when only the two most extreme outliers were removed and (4) became normally distributed by the Kolmogorov-Smirnov test ($p > 0.2$) when only the three most extreme outliers were removed.

Over all of these non-normally distributed series, only six outliers were removed. They constituted less than 2.1% of the data in each series. Four of these participants who contributed outliers occurred in only one of the three non-normal series, while the other two participants contributed outliers to two of the series. The outliers occurred in measurements with the RAF Rule equally as often as in measurements with the TRU.

Therefore it was considered acceptable to analyse the data as if it resembled normal distribution. The sample was large enough to support that assumption (Pallant, 2013). Furthermore, Bland and Altman (1999) state that slight departures from normality do not significantly diminish the robustness of analysis by difference plotting.

5.2 Repeatability of methods

Measurements were repeated with each method in the same conditions within a measurement session. The variation on repeating measurement was assessed, to gain an indication of the method's repeatability. If possible variation in AoA within such short timescales, as discussed in Section 6.6.6, were known, it would be deducted.

5.2.1 Repeatability of the RAF Rule

In Session 1, two measurements were made by the principal investigator with the RAF Rule for each participant. The mean of all these 286 measurements of AoA was 8.46D (range 3.1 to 17.2D). Their BMPV(95%) as defined in Section 4.2 was ±15.29%. However, the second reading did not resemble a normal distribution (Kolmogorov-Smirnov test, $p = 0.016$) without deleting the two uppermost outliers (participant numbers 109 and 135). When RAF Rule data for these two participants was excluded, the BMPV(95%) became ±15.18% and the data resembled a normal distribution (Kolmogorov-Smirnov test, $p = 0.074$).

The means of the two data-series were then compared by a paired-samples t-test. The t-test showed that, for the two measurements made by the principal investigator with the RAF Rule for each participant, the difference between the means of these two data series (mean R1 = 136.7mm, mean R4 = 133.1mm) had weak statistical significance (p

= 0.053) and Figure 5.3 shows weak agreement between the two series, with 95% limits of agreement between them estimated as ±2.56D.

5.2.2 Repeatability of the TRU

Five measurements of the near point were made with the TRU for each the 143 participants in Session 1. Each of these 715 measurements was converted to dioptres, the supplementary lens powers were subtracted, and testing showed that they could be described as normally distributed (Kolmogorov-Smirnov $p > 0.200$).

Measurement conditions differed a little (mainly in that a trial frame was worn for all but the first measurement) and measurements of T1 and T3u were about ten minutes apart. To assess whether this might have had any effect, a paired-samples t-test was used to compare T1 and T3u which were the first (mean = 178mm) and last (mean = 179mm) of the five conditions. This test did not show a significant difference between the means ($p = 0.75$). Their 95% limits of agreement were ±1.69D as shown in Figure 5.4.

Each measurement condition formed a group of 143 results. The five group means were compared by one-way repeated measures Analysis of Variance (ANOVA) which showed that there was no significant difference between the group means ($p = 0.077$).

The mean of all 715 AoA measurements using the TRU in Session 1 was 6.15D (range 1.5 to 12.3D). Their BMPV(95%) was ±11.93%.

In the ancillary investigation described in Section 4.2.2, repeated measures of the height of the smallest TRU letter discernible, at the near point and at about a metre, were obtained. At the near point the BMPV(95%) was ±12.00% and the data series did not resemble a normal distribution (Kolmogorov-Smirnov test, $p < 0.001$). The non-parametric Friedman test showed that the medians varied from each other ($p < 0.002$) with no clear influence revealed by the ranking of data in groups. However, when the TRU was viewed well beyond the near point the BMPV(95%) of the height of the smallest TRU letter discernible improved to ±6.30% and the data resembled a normal distribution by the Shapiro-Wilk test ($p = 0.57$) showing test-retest 95% limits of agreement of ±1.89 letters.

5.2.3 Repeatability of the autorefractor

The four measurements were made under the same conditions except that the fourth was attempted with the visual object held by the participant. As explained in Section 5.1, 93 participants each gave the first three readings (the other 18 participants' readings showed a similar range and distribution) and 72 provided all four.

In the 93 sets of three measurements (ie 93 x 3 = 279 measurements) recorded with the TRU mounted on the autorefractor rail, their range was from 1.1 to 9.2D with a mean of 5.63D. Each of the three data series resembled a normal distribution (Kolmogorov Smirnov $p > 0.09$).

The 95% limits of agreement between the first and last of the three measurements were ±0.79D as shown in Figure 5.5. The BMPV(95%) of the three measurements was ±7.14%.

The 279 measurements were further assessed by one-way repeated measures ANOVA. This showed ($p=0.983$) that the means of the three sets of measurements did not differ significantly.

During AoA measurement, there was no impression that autorefractor results were affected by angular deviation of the measurement axis from the visual axis when the participant was viewing letters on the TRU that were in positions furthest off-axis. This impression was supported by the results of Kundart *et al*. (2011) who showed that the WAM-5500 was quite tolerant of such angular deviation, such that the magnitude of the angular deviation in this experiment would have had negligible influence on the results. Furthermore, the angle of deviation would have been larger at higher AoA but Figure 5.5 does not show lower repeatability at higher levels of accommodation and neither do the results of Kundart *et al*.

5.2.4 Comparing repeatability of the RAF Rule with that of the TRU

Measurements taken at the start of Session 1, and repeated approximately fifteen minutes later at the end of the session, are compared in Figure 5.3 for the RAF Rule and in Figure 5.4 for the TRU. The results are summarised in Table 5.1, showing mildly better repeatability (intrasession mean CV) for the TRU than for the RAF Rule.

Table 5.1 AoA measurements in dioptres by both methods at the start and end of the Session 1 (n = 143)

method	mean	max	min	SD	CV %	normality*
RAF Rule start	8.28	16.7	3.15	2.69	32.5	
end	8.63	17.2	3.14	2.97	34.4	0.016 [1]
Intrasession mean CV = 7.86 (SD 7.75)						
TRU start	6.24	11.2	2.12	1.87	30	
end	6.21	12.2	1.79	1.82	29.3	
Intrasession mean CV = 6.98 (SD 6.20)						

* Kolmogorov-Smirnov test, p if not >0.05

[1] 0.074 if excluding data of participants 109 and 135, the two most outlying in this series

Extreme changes with each method were also compared, by contrasting the percentage of the smaller to the larger reading obtained with each method for all 143 participants. 26 of the 143 participants (18%) showed very good repeatability, within 3%, for either method. At its other extreme, repeatability was larger (ie worse) than 30% for 12 participants (13%) with the RAF Rule and for five participants (3%) with the TRU.

The mean increase from the start to the end of the session was 0.35D for the RAF Rule and -0.02D for the TRU. The difference between these two increases' means was statistically significant (p = 0.033 by paired t-test) but its clinical significance is debatable.

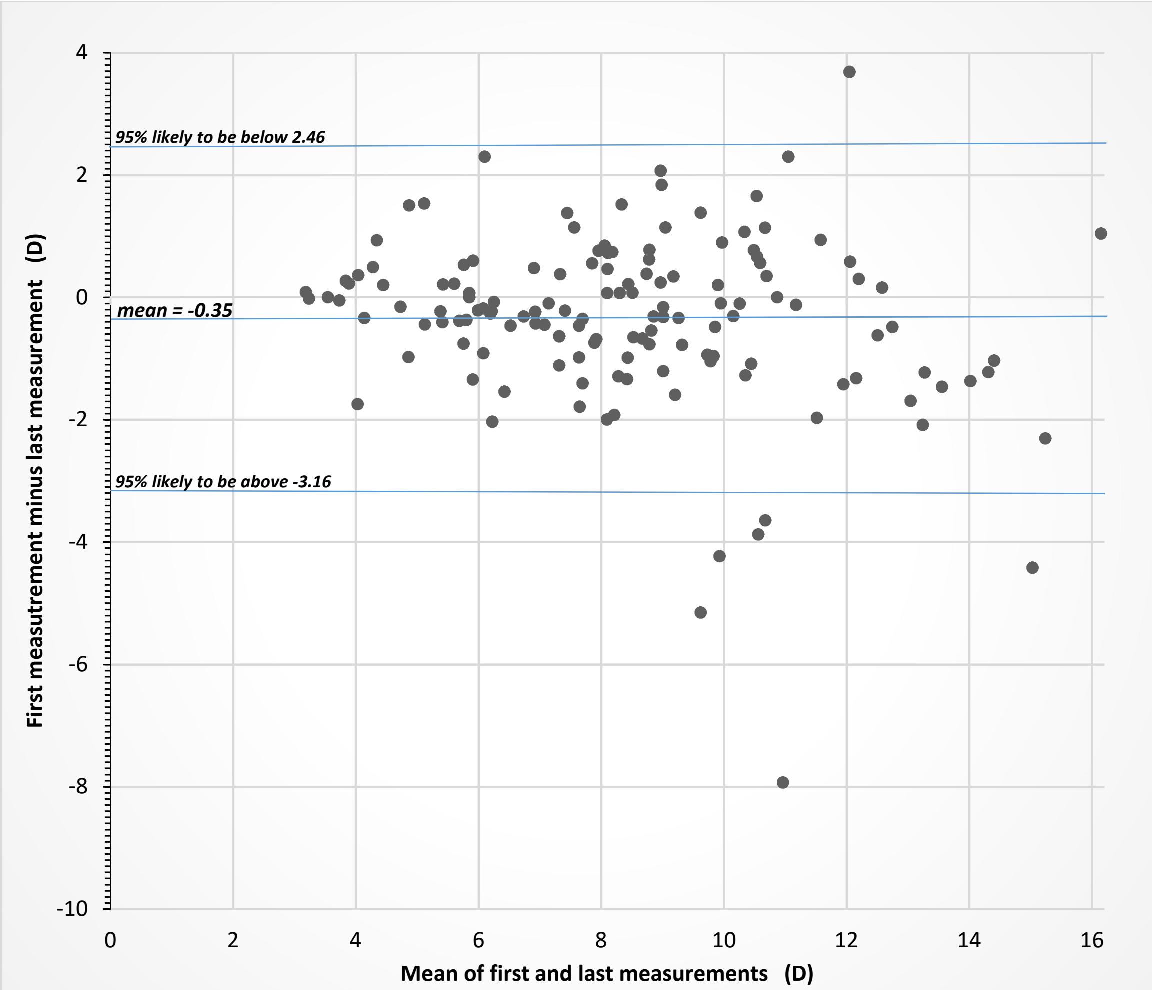

Figure 5.3 Difference plot of RAF Rule measurements at the start and the end of Session 1 (n=143)

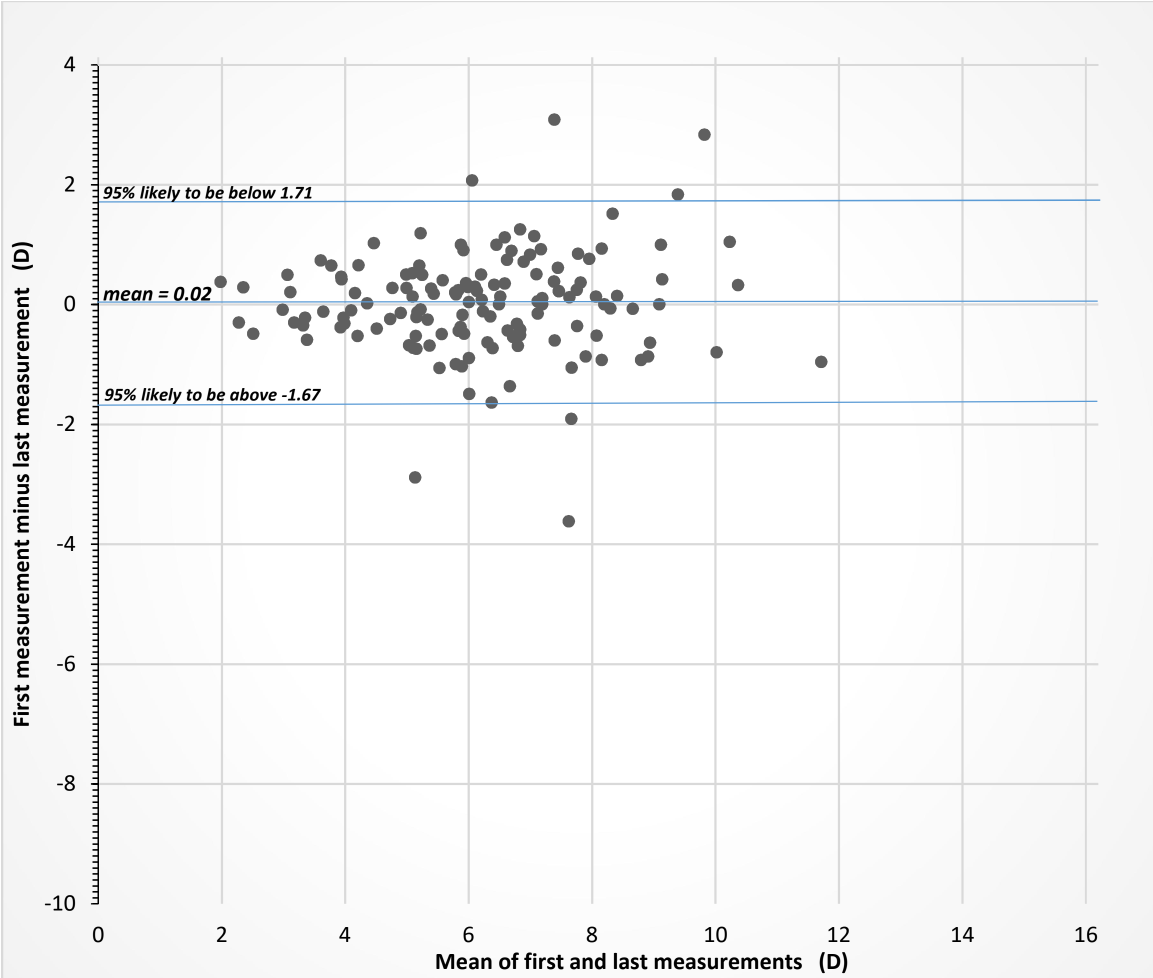

Figure 5.4 Difference plot of TRU measurements at the start and the end of Session 1 (n=143)

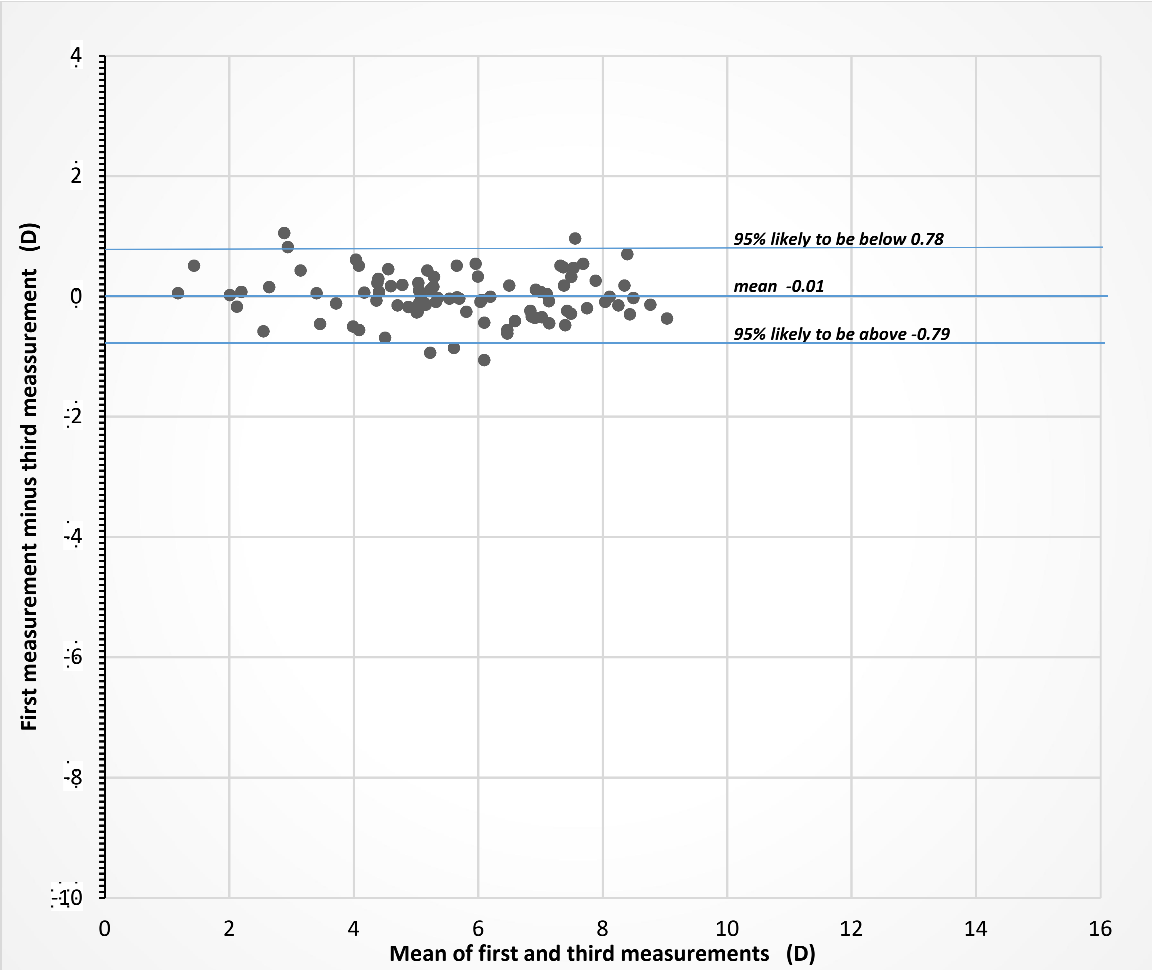

Figure 5.5 Difference plot of first and third autorefractor measurements (n=93)

5.3 Comparing results of the RAF Rule with those of the TRU

Figure 5.6 shows clearly the difference between results with these two methods in Session 1, as does Figure 5.7 for Session 2 though it shows mildly less difference. Estimated 95% confidence limits of agreement between the methods spanned 7.23 D in Session 1 and 4.99 D in Session 2.

Figures 5.6 and 5.7 show marked bias, in that the TRU tended to give lower results than the RAF Rule. They also show that the divergence between the methods' results increased with increasing RAF Rule measurements.

This bias was analysed further by dividing the mean RAF Rule result by the mean TRU result for the 254 comparisons (143 in Session 1, plus 111 in Session 2). These ratios were distributed normally (Kolmogorov-Smirnov p > 0.2) and averaged 1.39 (SD = 0.26) in Session 1 and 1.32 (SD = 0.20) in Session 2. 240 of them (94.5%) gave a lower measurement with the TRU than with the RAF Rule. Of the remaining fourteen who gave higher AoA readings with the TRU than with the RAF Rule, ten were at lower than the average level of AoA for the 254 comparisons.

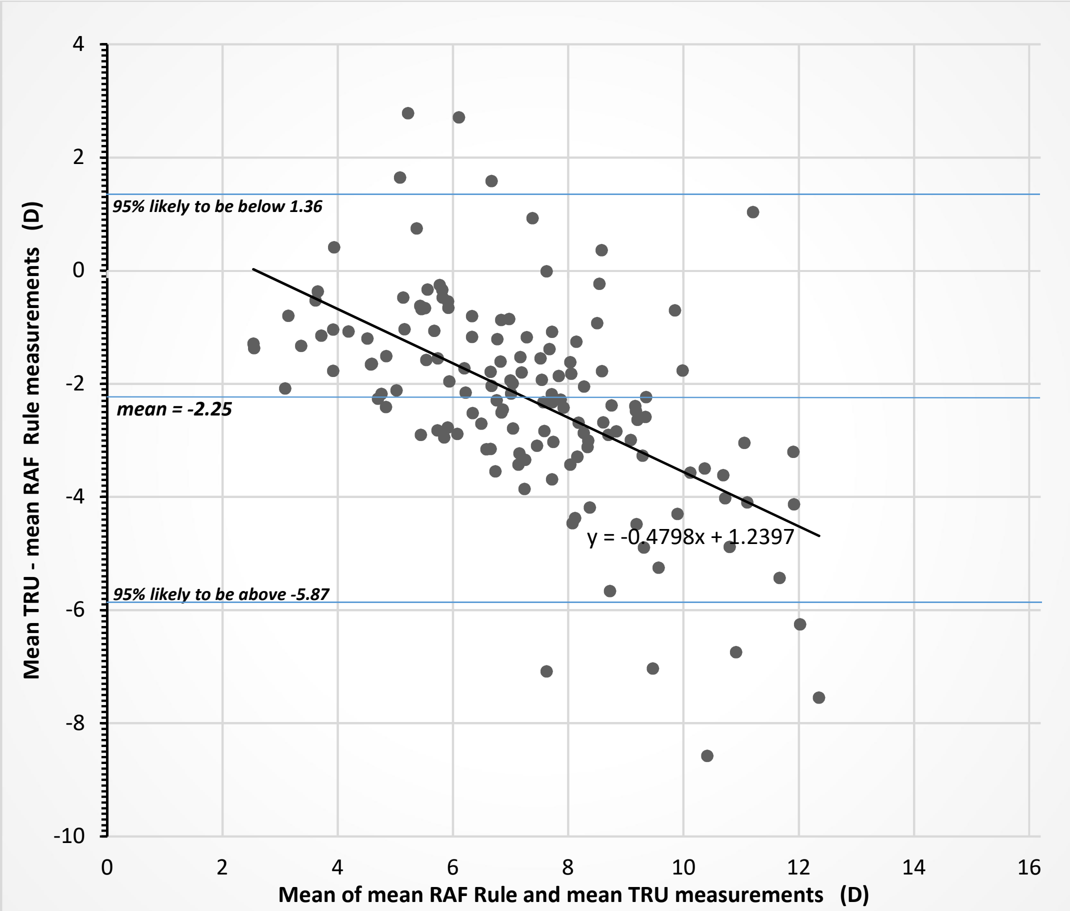

Figure 5.6 Difference plot of RAF Rule and TRU measurements from Session 1 (n=143) showing regression line, slope = -0.48

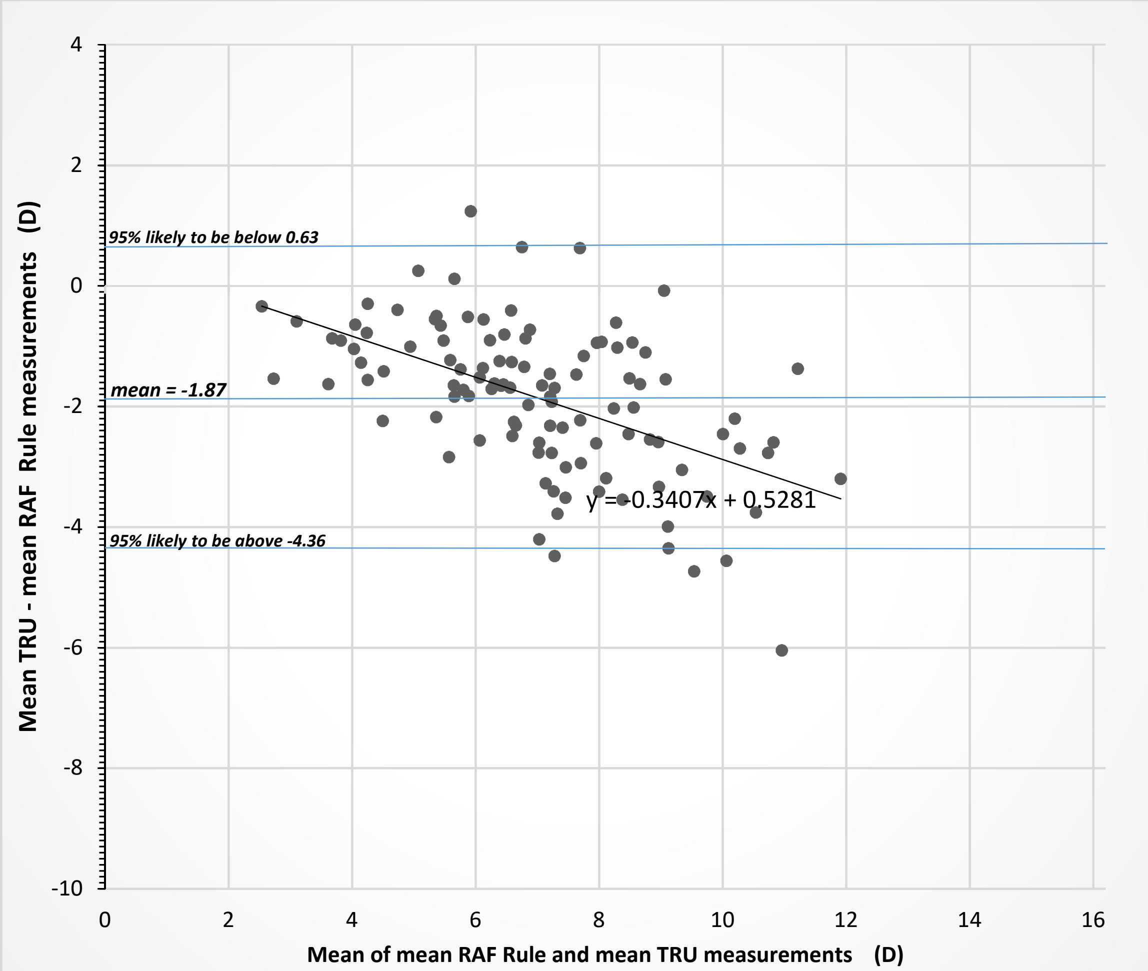

Figure 5.7 Difference plot of RAF Rule and TRU measurements from Session 2 (n=111) showing regression line slope = -0.34

Tm1 and Rm1 were replotted in Figure 5.8 (and Tc5 and Rc5 in Figure 5.9) to show how the disparity between the two methods' results varied with the level of each method's result. They show that the disparity tended to be higher with higher RAF Rule results but lower with higher TRU results. They also show that this variation of disparity was greater when plotted against RAF Rule results than TRU results.

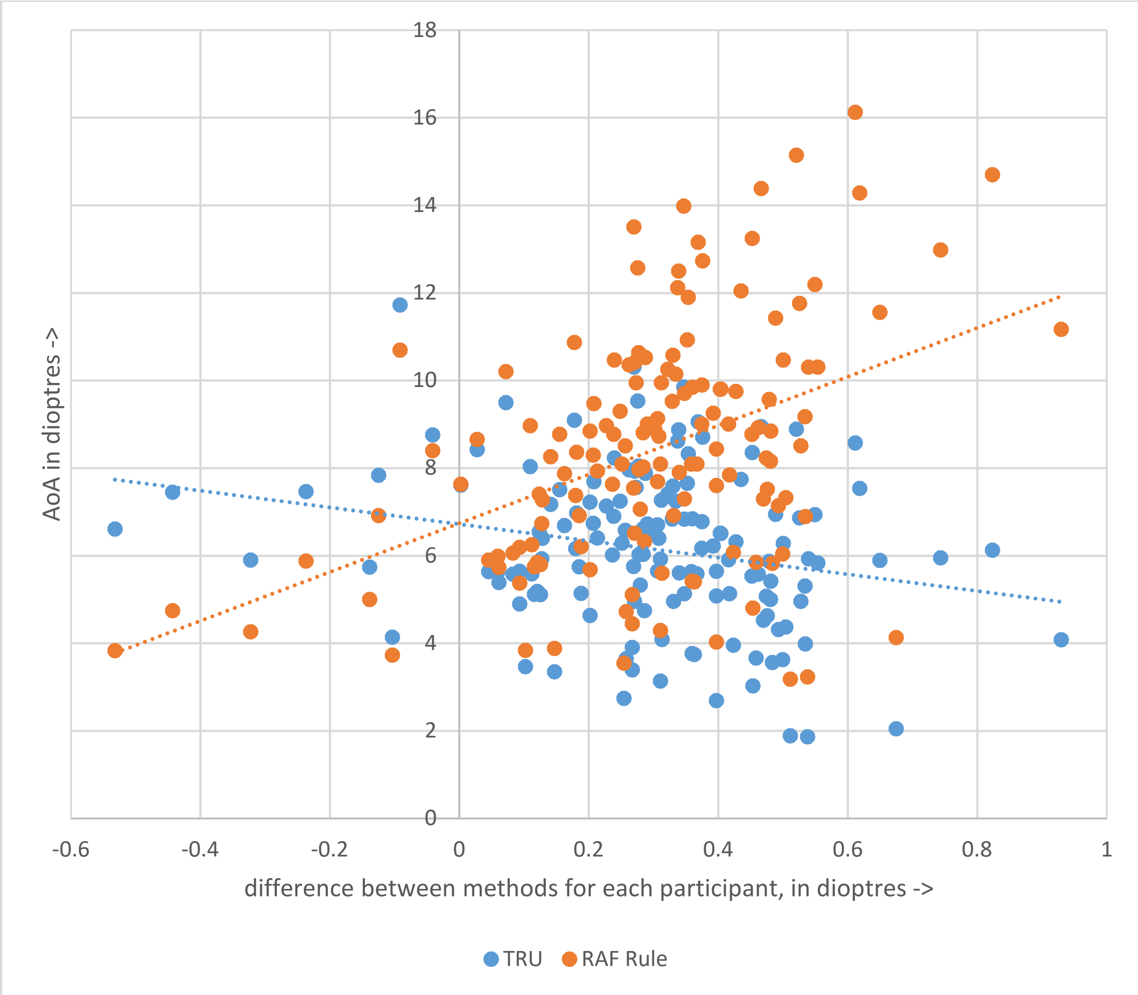

Figure 5.8 Difference between RAF Rule and TRU measurements compared to their mean, from Session 1 (n=143)

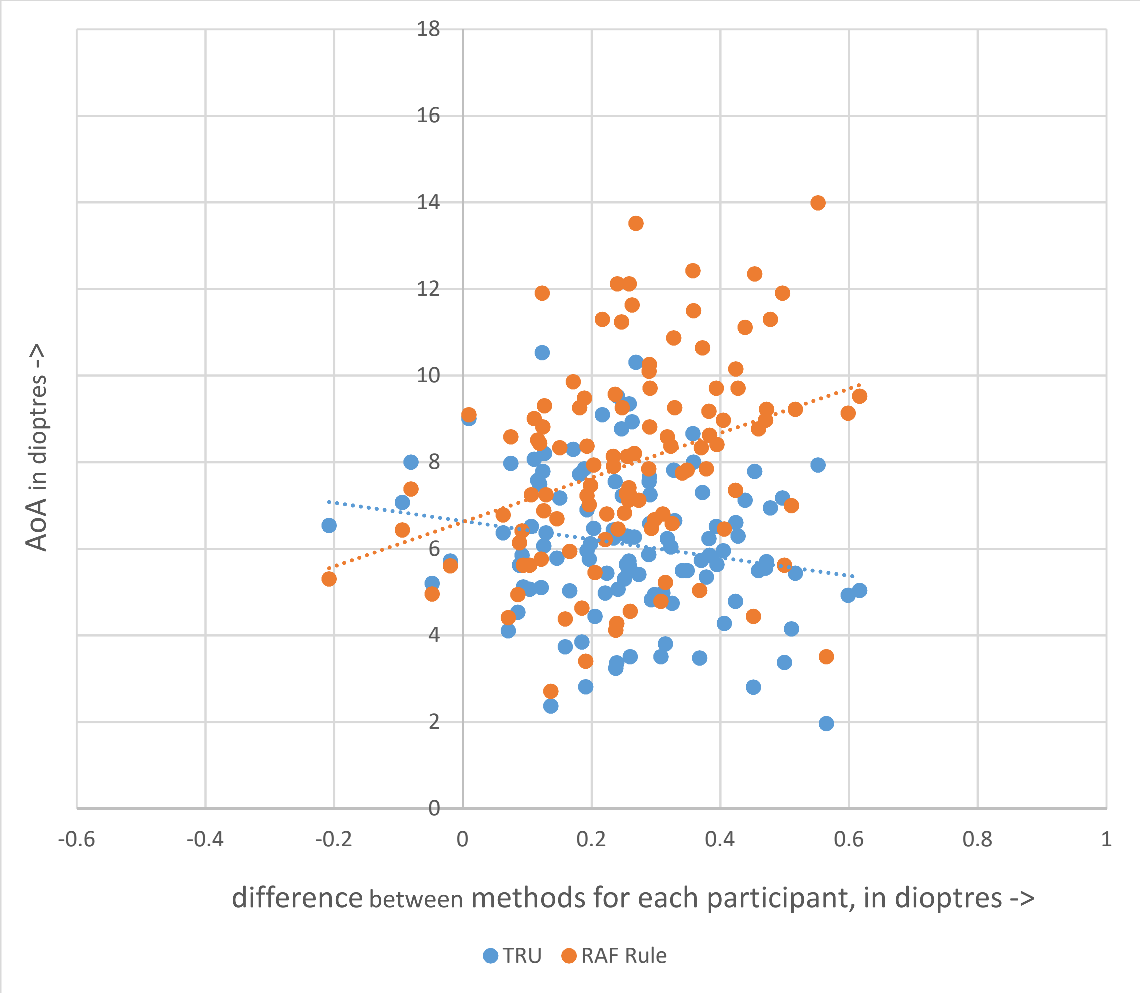

Figure 5.9 Difference between RAF Rule and TRU measurements compared to their mean, from Session 2 (n=111)

5.3.1 Comparing the RAF Rule and the TRU for reproducibility between sessions

110 participants gave repeated measurement data in Session 2. The time between sessions varied between one week and one year, the average being twelve weeks (SD sixteen weeks) and 62% being within three weeks. Measurements in Session 2 were adjusted for likely loss of AoA due to age since Session 1 as described in Section 4.5.1.

The change in mean AoA measurements between Sessions 1 and 2, with either method (Tm1 – Tc5 and Rm1 – Rc5) appeared unrelated to the length of time between the sessions. This appeared clear on scatterplots of AoA against time between sessions, and Pearson correlation (r = -0.07 for the TRU and 0.09 for the RAF Rule).

The results for change between sessions are summarised in Table 5.2. The two methods' reproducibility between sessions was compared by contrasting the change in mean measurement between sessions with each method. This change is expressed in Table 5.2 as a CV as defined in Section 4.2.

Table 5.2 AoA measurements in dioptres, by RAF Rule and by TRU in both sessions, for the 110 participants who gave all those data

method	**mean**		**max**	**min**	**SD**	**CV%**
RAF Rule						
Session 1	8.57		16.1	3.18	2.59	30.2
Session 2	8.19		14.3	2.51	2.54	31.0
Inter-session mean CV =	10.80% (SD 8.52%)					
TRU						
Session 1	6.3		11.7	1.89	1.74	28.9
Session 2	6.07		10.5	1.97	1.68	27.7
Inter-session mean CV =	6.69% (SD 5.39%)					

The distribution of each of these data-series approximated to a normal distribution by the Kolmogorov-Smirnov test, ($p > 0.05$).

Extreme changes between sessions were also compared, by contrasting the ratio of the larger to the smaller reading of a pair. With the RAF Rule 5% of pairs of readings had a ratio above 15.2% of the larger to the smaller reading, as against 9.0% with the TRU.

Figures 5.10 and 5.11 contrast the measurements in each session for each of the two methods. The data points represent the means of readings that were taken for each participant with one method by the principal investigator. They show substantially better reproducibility for the TRU than for the RAF Rule.

A subsidiary finding shown in Figures 5.10 and 5.11 is that results tended to decrease from Session 1 to Session 2, by a mean of 0.38D with the RAF Rule and 0.23D with the TRU. This would contrast with the mean intrasession increase of 0.35D shown for the RAF Rule in Section 5.2.4, but the difference between the two methods' intersession changes was not statistically significant (paired t-test $p = 0.33$).

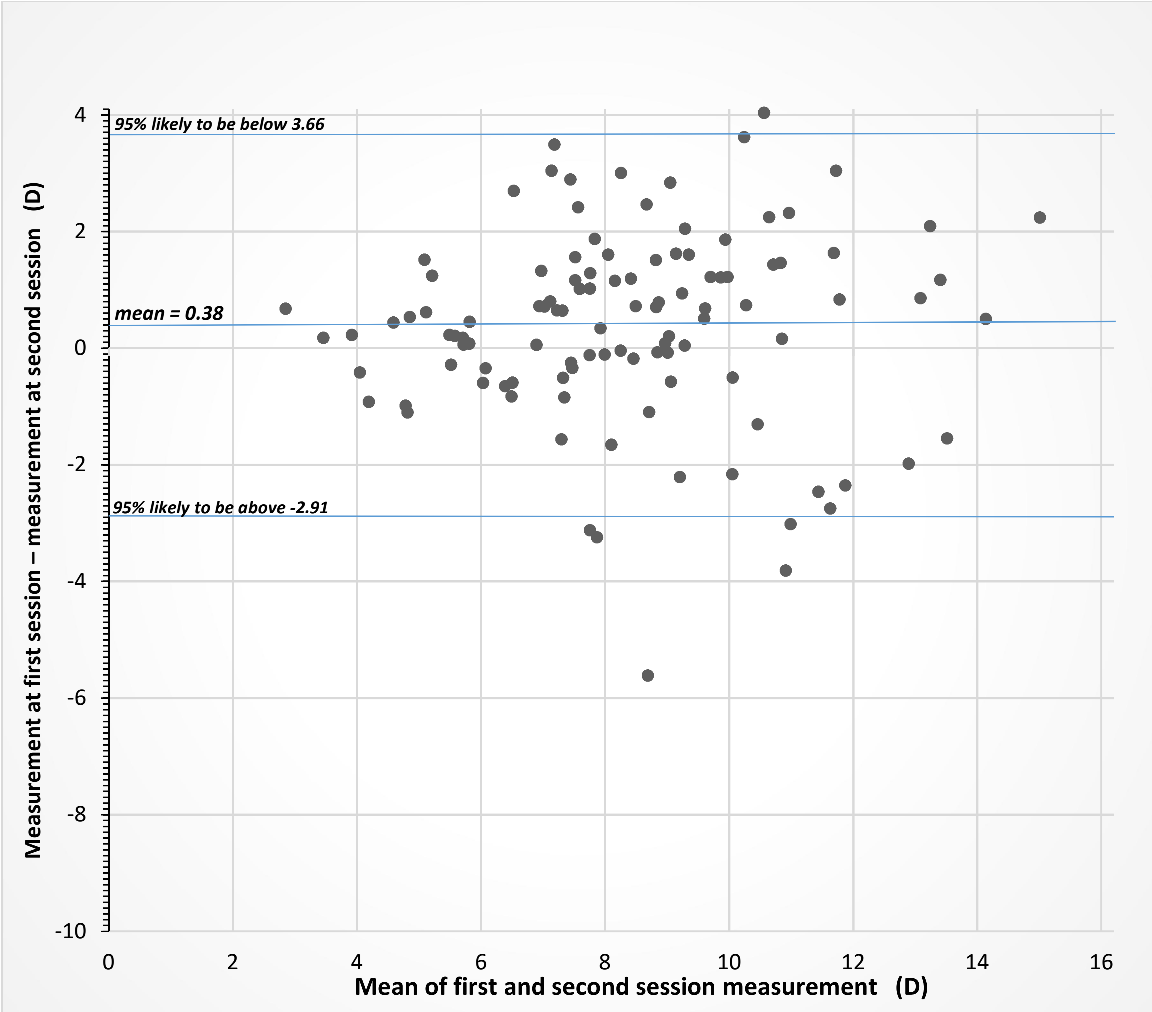

Figure 5.10 Difference plot of mean RAF Rule measurements in Session 1 with those in Session 2 (n=110)

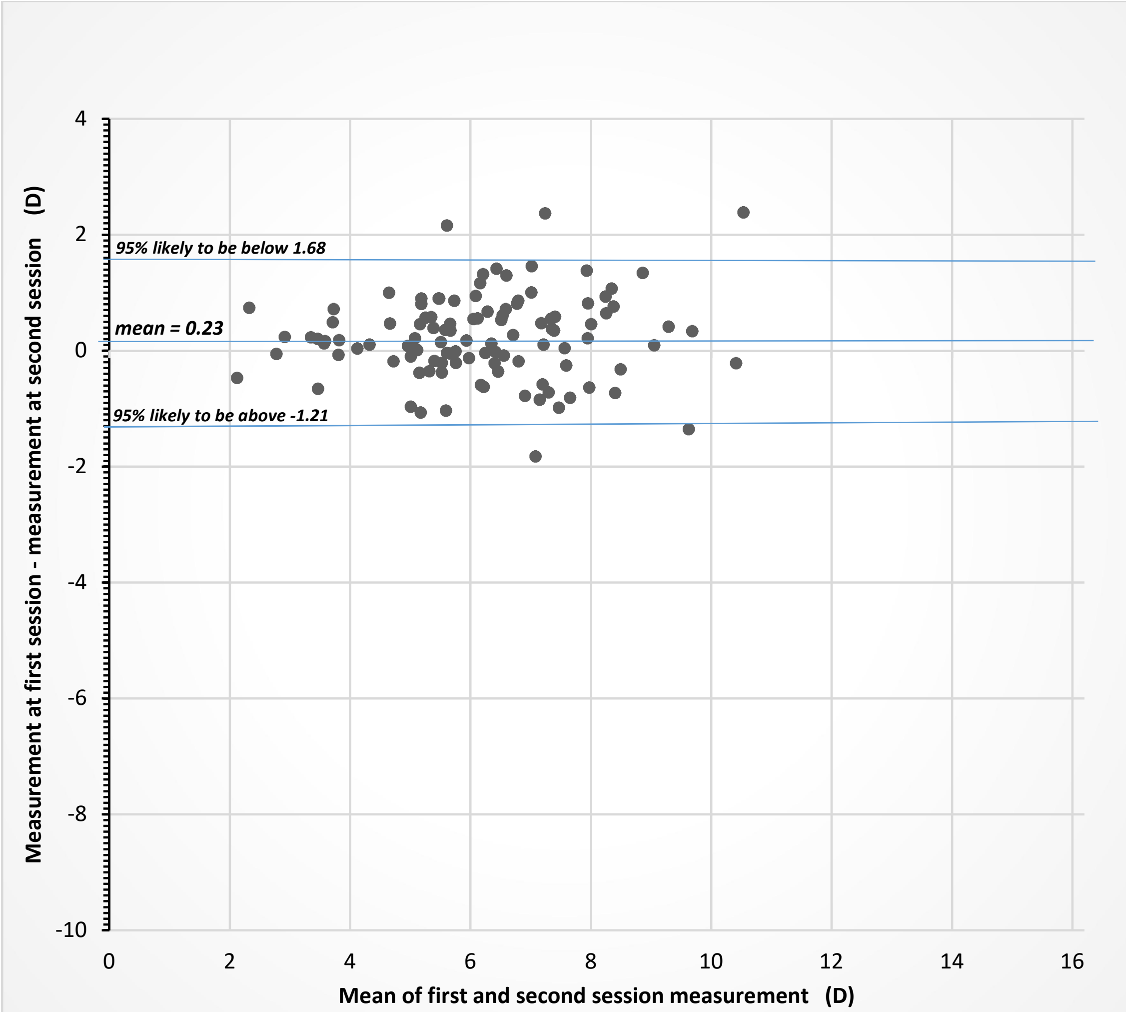

Figure 5.11 Difference plot of mean TRU measurements in Session 1 with those in the Session 2 (n=110)

5.3.2 Comparing the RAF Rule results with those of the TRU, for reproducibility between investigators

This assessed the variability of results arising from the same measurement being made by different investigators. The 111 participants in Session 2 were measured by two investigators who used the same two methods of measurement as at the start of Session 1, under the same experimental conditions, but the smallest letter read on the TRU was not noted. The investigators were masked to each other's results. The set of four measurements was completed in about five minutes for each participant.

Their results are shown in Figures 5.12 and 5.13. The 95% confidence limits show that agreement between the investigators was ±2.55 D for the RAF Rule and ±1.28 D for the TRU. The principal investigator's results were, on average, 0.05 D lower than the secondary investigator's with the TRU, and 0.34 D higher with the RAF Rule.

The mean results for the two investigators, with the two methods were,

for the primary investigator and for the secondary investigator

RAF Rule: 7.33 D *TRU:* 5.54 D *RAF Rule:* 7.10 D *TRU:* 5.55 D

The four data series were each approximately normally distributed by the Kolmogorov-Smirnov test ($p > 0.19$) so the investigators' mean results were compared by paired-samples t-testing. This showed no significant difference between the mean AoA determined by the two investigators for the TRU ($p = 0.882$) but a significant inter-investigator difference between the two investigators' mean results for the RAF Rule ($p = 0.041$).

Figures 5.12 and 5.13 suggest that the agreement between investigators did not overall appear to depend significantly on the level of the measurement, except that in higher AoA results using the RAF Rule the principal investigator's measurements showed a small tendency to be slightly higher than the secondary investigator's, while a smaller opposite effect occurred with the TRU. Results, which resembled a reasonably normal distribution (Kolmogorov-Smirnov test, $p > 0.2$) showed negligible correlation between the difference between investigators and the level of measurement, with Pearson correlation coefficient $r = 0.26$ for the RAF Rule and -0.13 for the TRU. A slightly stronger correlation emerged for mean RAF Rule results above 6.82D, where $r = 0.40$ (0.14 at lower levels).

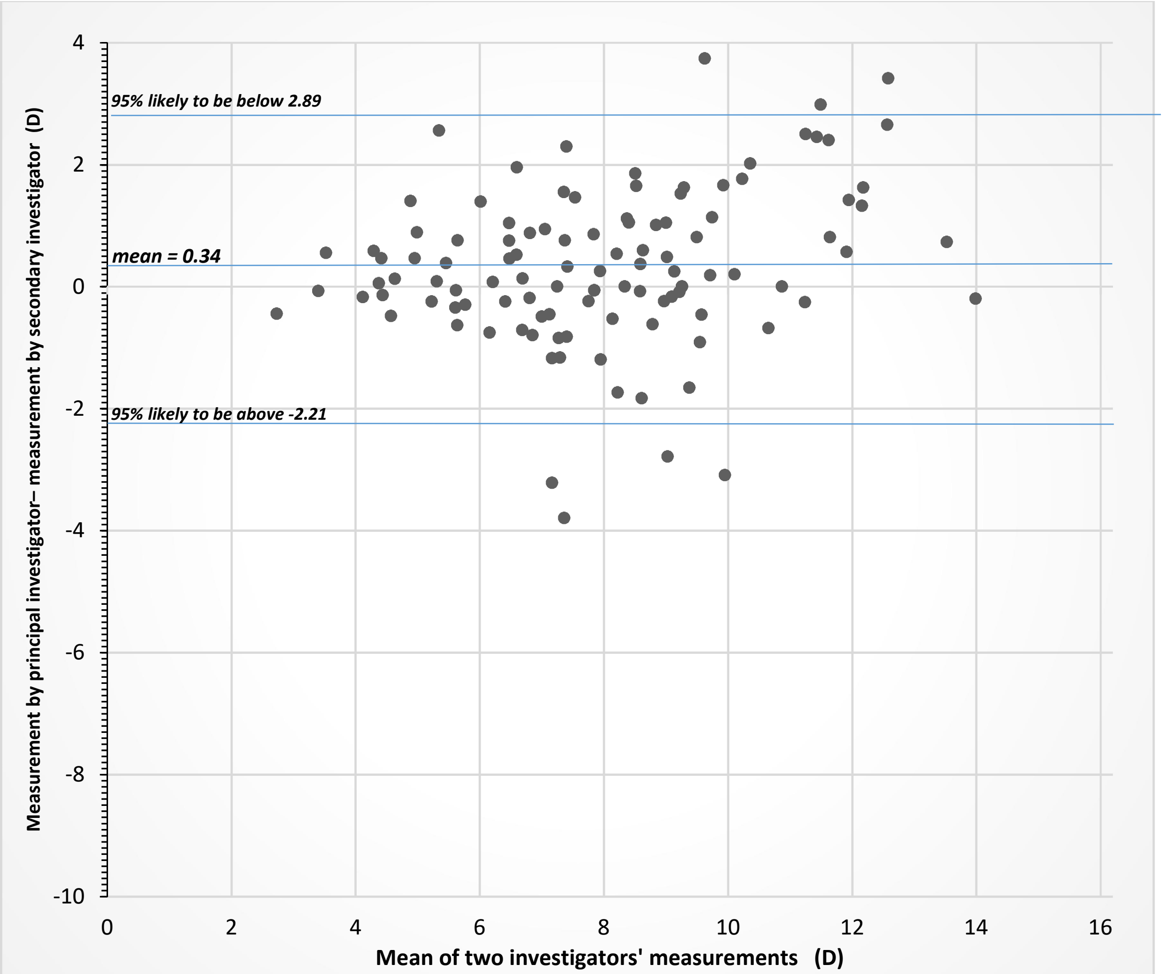

Figure 5.12 Difference plot between the two investigators' RAF Rule measurements (n=111)

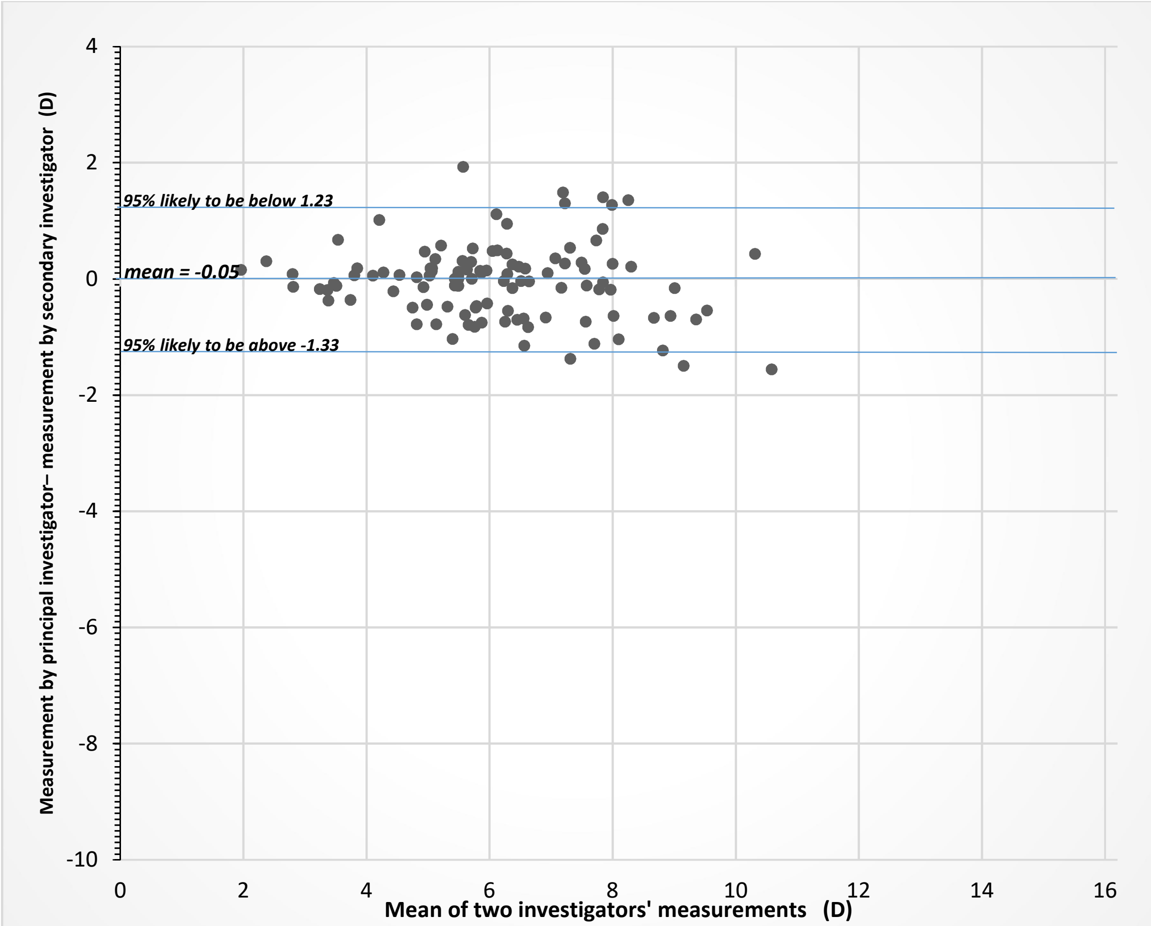

Figure 5.13 Difference plot between the two investigators' TRU measurements (n=111)

The two investigators' differences in Session 2 between results for the RAF Rule and the TRU was also compared. The ratio of the results with each method for each participant showed a statistically significant difference between the two investigators, by paired t-test ($p = 0.030$) and by comparison of Figures 5.14 and 5.15 which show that agreement was slightly better for the secondary investigator. Figures 5.14 and 5.15 also show that the principal investigator's results for the RAF Rule tended to be higher than the secondary investigator's at higher AoA.

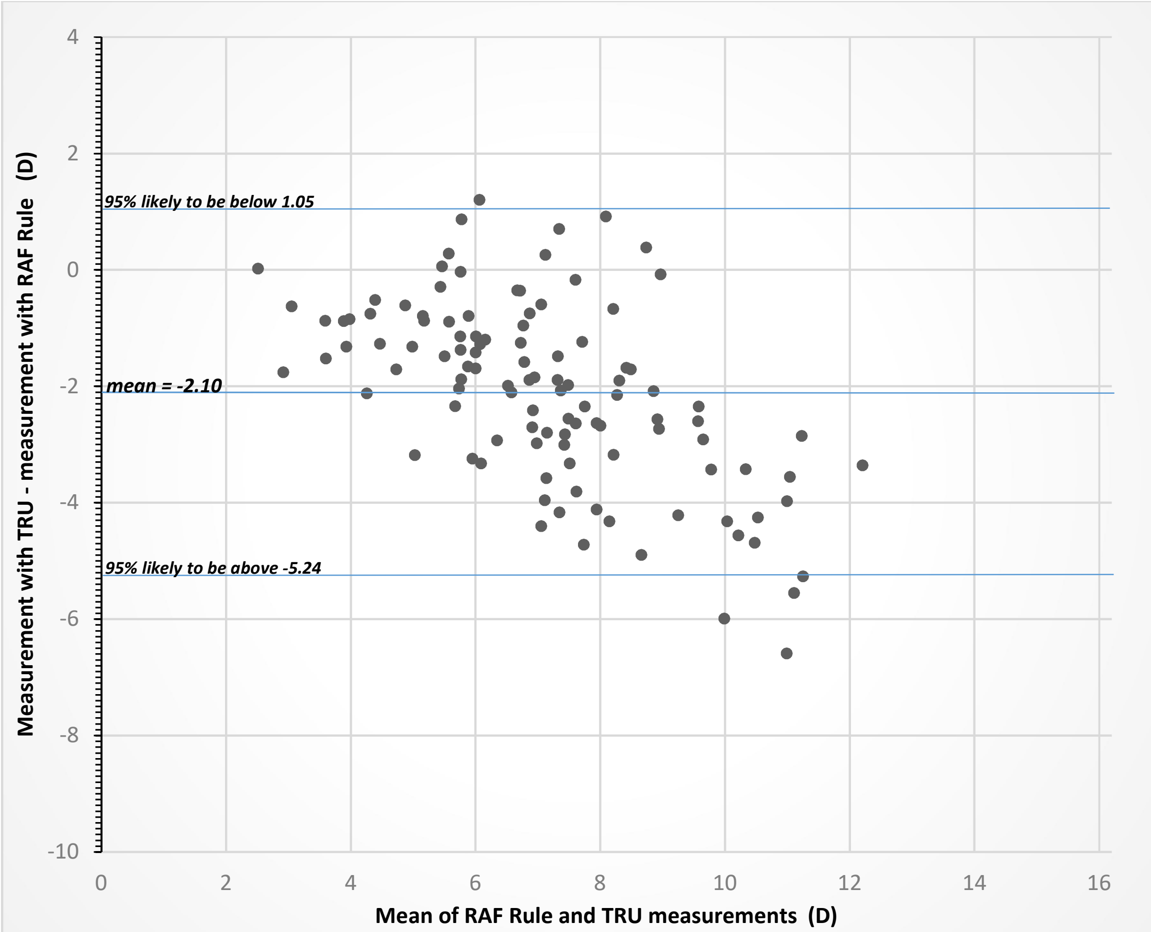

Figure 5.14 Difference plot between the two methods for the principal investigator, in Session 2 (n=111)

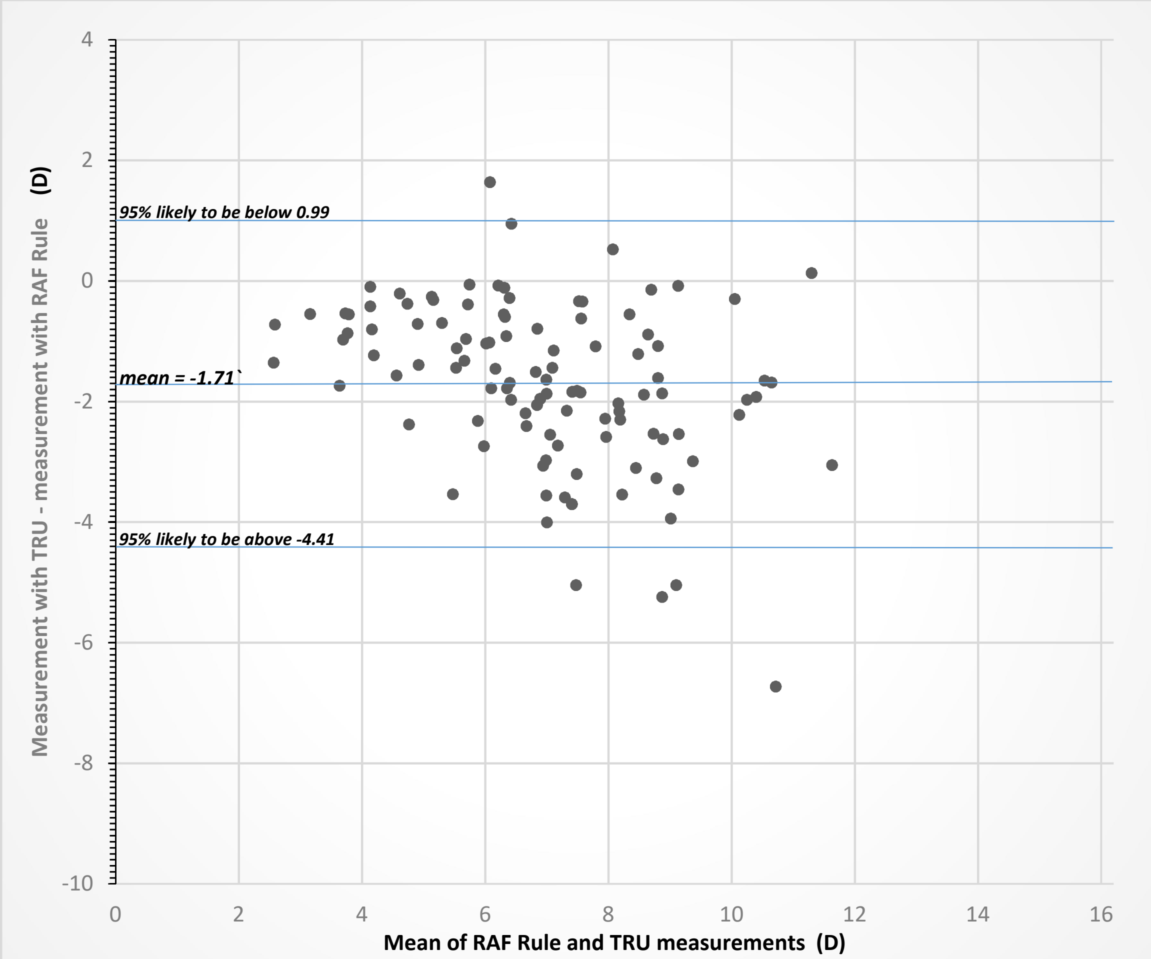

Figure 5.15 Difference plot between the two methods for the secondary investigator (n=111)

5.3.3 Comparing results with the RAF Rule, and the TRU, with the autorefractor

A sample data-download from the autorefractor as described in Section 4.3.2.1 is shown in Figure 5.16, copied from the .CSV file of results produced by the instrument and displayed using Microsoft Excel, and shows some variation, without clear pattern, in successive autorefractor measurements. Figure 5.16 illustrates the variation It also shows some irregular gaps in the otherwise quite regular pattern of measurements that unfortunately tended to occur at high levels of accommodation. Inspection of the .csv file for each set of readings showed the maximum refractive power of the measured eye including its habitual refractive correction if any worn for the measurements. This maximum reading was adjusted for instrument calibration error, if any found as above, and any added minus lens power that had been required as described above was added. The result was then recorded as positive powers A1, A2, A3 and Ah for each measurement file, and a mean value A was taken of A1, A2 and A3.

The fluctuations would account for at least some of the variation, without clear pattern, in successive autorefractor measurements. Figure 5.16 illustrates the variation It also shows some irregular gaps in the otherwise quite regular pattern of measurements that unfortunately tended to occur at high levels of accommodation.

Figure 5.16 A sample of typical autorefractor output

Time (seconds)			Refractive error (D mean sphere)	Pupil diameter (mm)
43.45	R	FAR	-5	2.9
43.61	R	FAR	-4.72	2.9
43.89	R	FAR	-4.37	
44.11	R	FAR	-4.66	
44.27	R	FAR	-4.85	2.8
44.49	R	FAR	-4.66	2.8
44.71	R	FAR	-4.66	2.8
44.88	R	FAR	-4.42	2.8
45.1	R	FAR	-4.32	2.8
46.8	R	FAR	-4.52	
46.97	R	FAR	-4.62	
47.24	R	FAR	-4.87	2.8
47.41	R	FAR	-4.82	2.9
47.57	R	FAR	-4.97	2.8
47.79	R	FAR	-5.27	2.8
48.01	R	FAR	-5.08	2.7
48.18	R	FAR	-5.26	2.7
48.4	R	FAR	-5.06	2.6
48.62	R	FAR	-5.25	2.7
48.89	R	FAR	-4.4	
49.11	R	FAR	-4.56	
49.33	R	FAR	-4.9	2.9
49.5	R	FAR	-4.57	2.9
49.77	R	FAR	-4.33	
49.93	R	FAR	-4.4	
50.16	R	FAR		2.9
50.43	R	FAR	-3.98	
50.6	R	FAR		
50.87	R	FAR		
51.2	R	FAR		
51.42	R	FAR		
51.59	R	FAR		
51.81	R	FAR		
51.97	R	FAR		
52.25	R	FAR		
52.52	R	FAR		
52.74	R	FAR	8.14	

Figure 5.17 compares results (in Session 2) with the RAF Rule to results with the autorefractor, as in Figure 5.18 where results with the TRU replace those with the RAF Rule. They show that results with the autorefractor tended to be lower than those with either of the test methods, but to very differing extents. This bias was seven times greater for the RAF Rule (2.19D) than for the TRU (0.30D).

The variation between results with the autorefractor and those with the test methods was less with the TRU than with the RAF Rule. The standard deviation of differences between measurements with the TRU and the autorefractor was 58% of that for the RAF Rule. The estimated 95% limits of agreement between the autorefractor and the TRU spanned 3.01D, as against 5.20D between the autorefractor and the RAF Rule.

The difference between results with the TRU and those with the autorefractor, and proportionate agreement between the two methods, appeared independent of the mean results of the two methods. However, the amount by which the RAF Rule's results exceeded those of the autorefractor increased (and at a moderately increasing rate) with autorefractor readings above about 7D, as the regression line in Figure 5.17 shows. This effect is not shown by the regression line for the TRU in Figure 5.18 so it is probably attributable to a characteristic of the RAF Rule method.

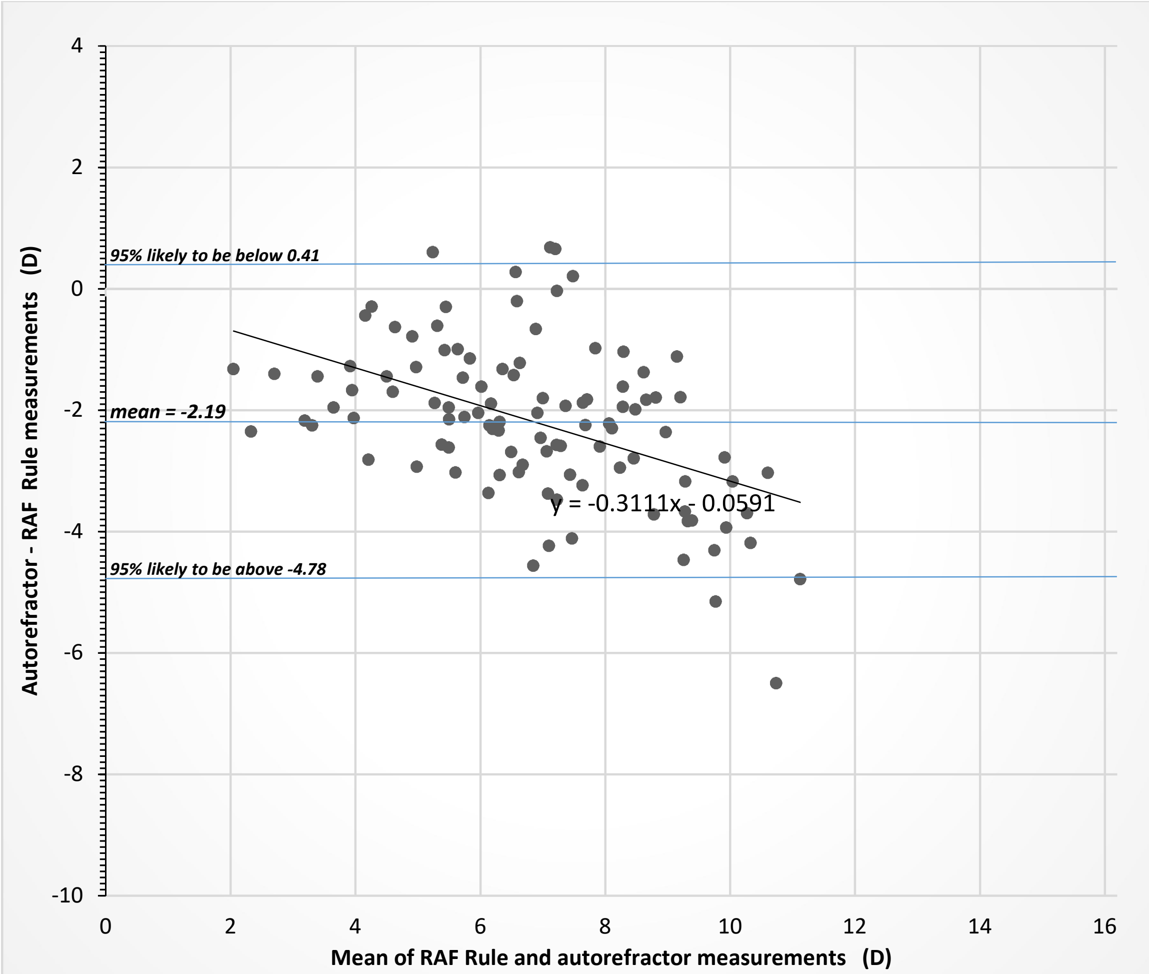

Figure 5.17 Difference plot between the RAF Rule and the autorefractor measurements (n=104) showing regression line slope = -0.31

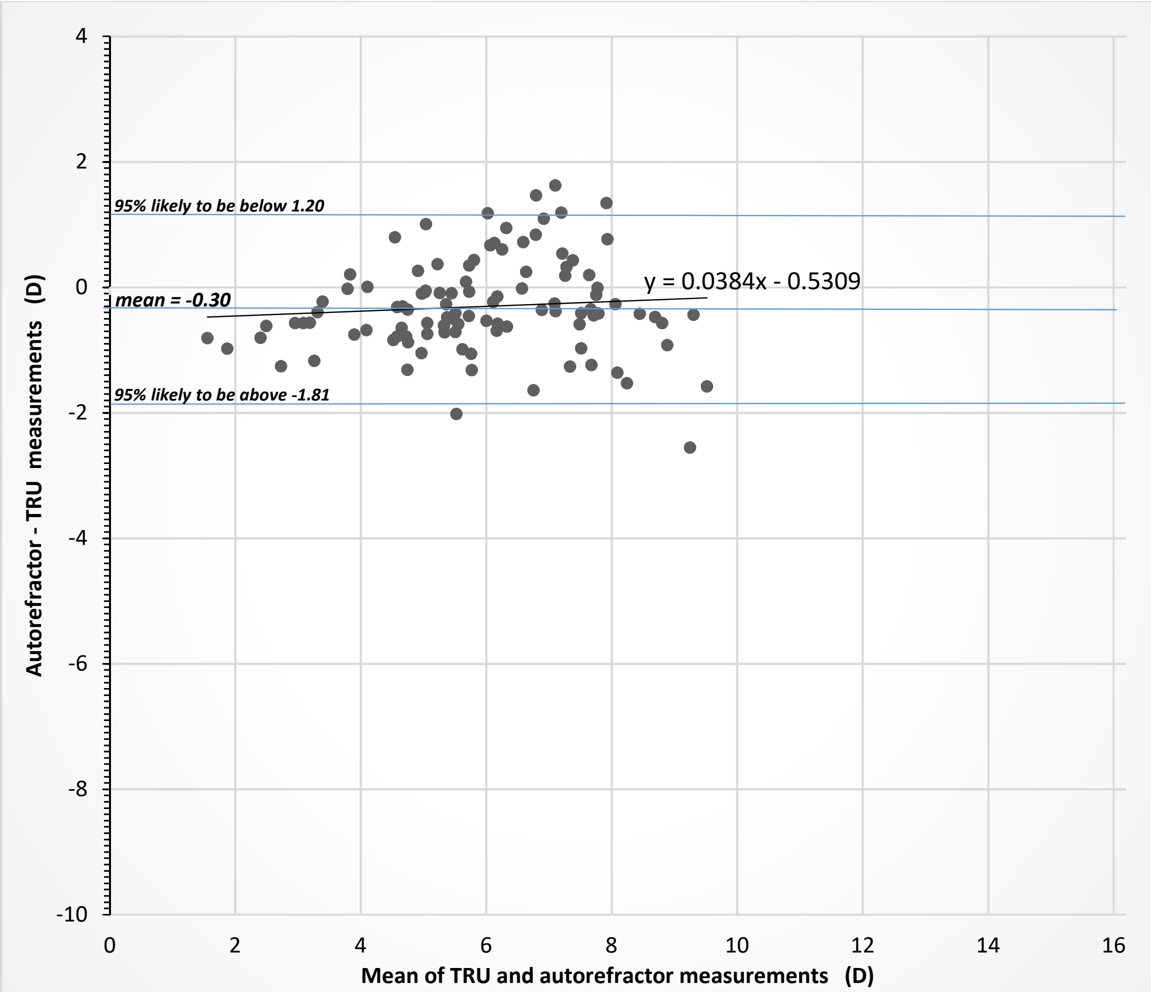

Figure 5.18 Difference plot between the TRU and the autorefractor measurements (n=104) showing regression line slope = 0.04

5.3.4 The effect on autorefractor measurements of how the TRU was held

The 288 AoA measurements for the 72 participants who gave all four readings with the autorefractor ranged from 2.0 to 9.2 D. They showed a slight preponderance around 5D, and closely approximated a normal distribution (Kolmogorov-Smirnov test, $p > 0.2$).

There was a mean decrease of 0.25D in AoA measurement when the TRU was handheld (mean decrease 4.7%, SD 7.9%) and handheld autorefractor measurement correlated well with non-handheld autorefractor measurements ($r = 0.98$). The difference between the mean measurement when the target was handheld, and when it was not, was significant statistically ($p < 0.0001$ by paired two-sample t-test). Figure 5.19 shows that this decrease in measurement did not appear to have been influenced by the level of the measurement.

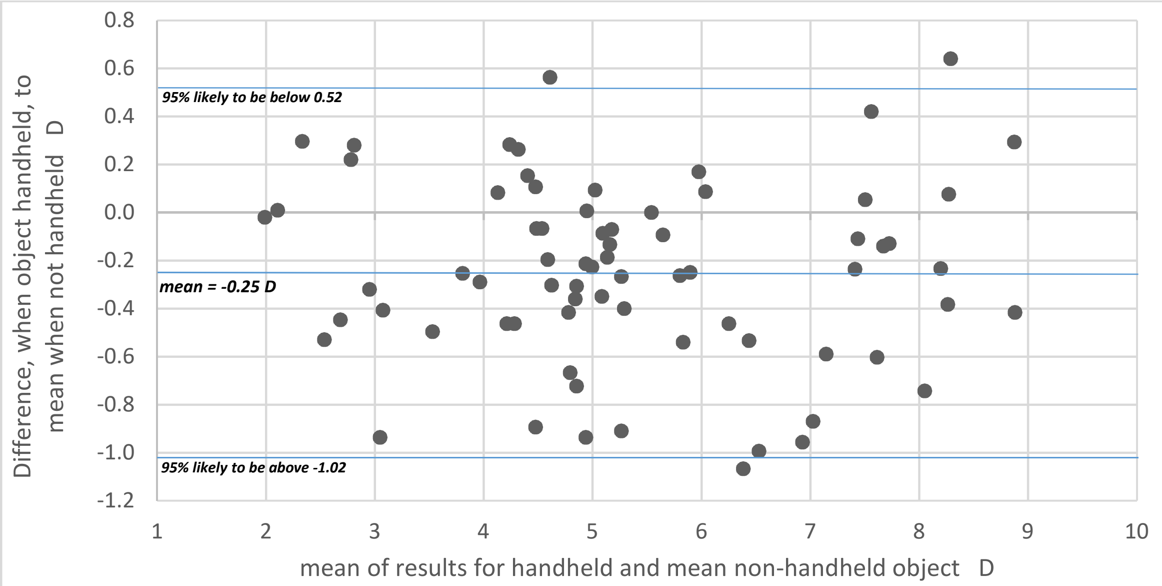

Figure 5.19 Difference plot of autorefractor measurement of the mean AoA when the object was handheld and when the object was mounted on the autorefractor

5.4 Visual acuity at the near point, and its comparison to visual acuity one-sixth beyond the initial near point

T and H at the near point were recorded five times in one experimental session for each of 143 participants. One participant's results were excluded as a clear outlier by Grubbs' test. This was participant number 66, whose mean VN was 293 which was more than six SDs from the mean for all participants, although participant 66's data resembled that for an average participant in its similarity of visual acuity measured at the near point to that measured slightly further away.

Excluding the results of participant 66 gave 710 measurements (five for each of 142 participants) of visual acuity at the near point (VN). They ranged from 443 to 1614 with a mean of 903 and a standard deviation of 189, and approximated a normal distribution (Kolmogorov-Smirnov p = 0.097: while, by the same test, each of the five series more closely resembled a normal distribution).

The possibility of a practice or a fatigue effect in this measurement of VN was investigated by comparing the means of the five groups of 142 acuity measurements, using single-factor repeated measures ANOVA. This showed that there was no significant difference between the group means ($p = 0.285$) demonstrating no significant overall trend of change in VN.

The mean VN for each participant was compared with the VA when the distance from the corneal vertex was increased by one-sixth of the initially-measured near point's distance from the eye. The latter VA series also approximated a normal distribution (Kolmogorov-Smirnov $p>0.2$) but did not relate closely to VN as the following findings show. The comparison, shown in Figure 5.20, showed a small mean decrease in VA on moving the TRU away, but with wide variation and no clear relationship between the near-point acuity found with the TRU (mean = 903) and the acuity one-sixth further away (mean = 919). A paired samples t-test showed a significant difference ($p = 0.041$, one-tailed as VA was unlikely to improve at the near point) between the means of these two measurements and the correlation coefficient between these two VA series was unimpressive (Pearson $r = 0.787$). Furthermore, the data series for H at one-sixth further than the near point did not resemble a normal distribution ($p < 0.0001$ by the Kolmogorov-Smirnov test) quite unlike the corresponding series for VA and for T.

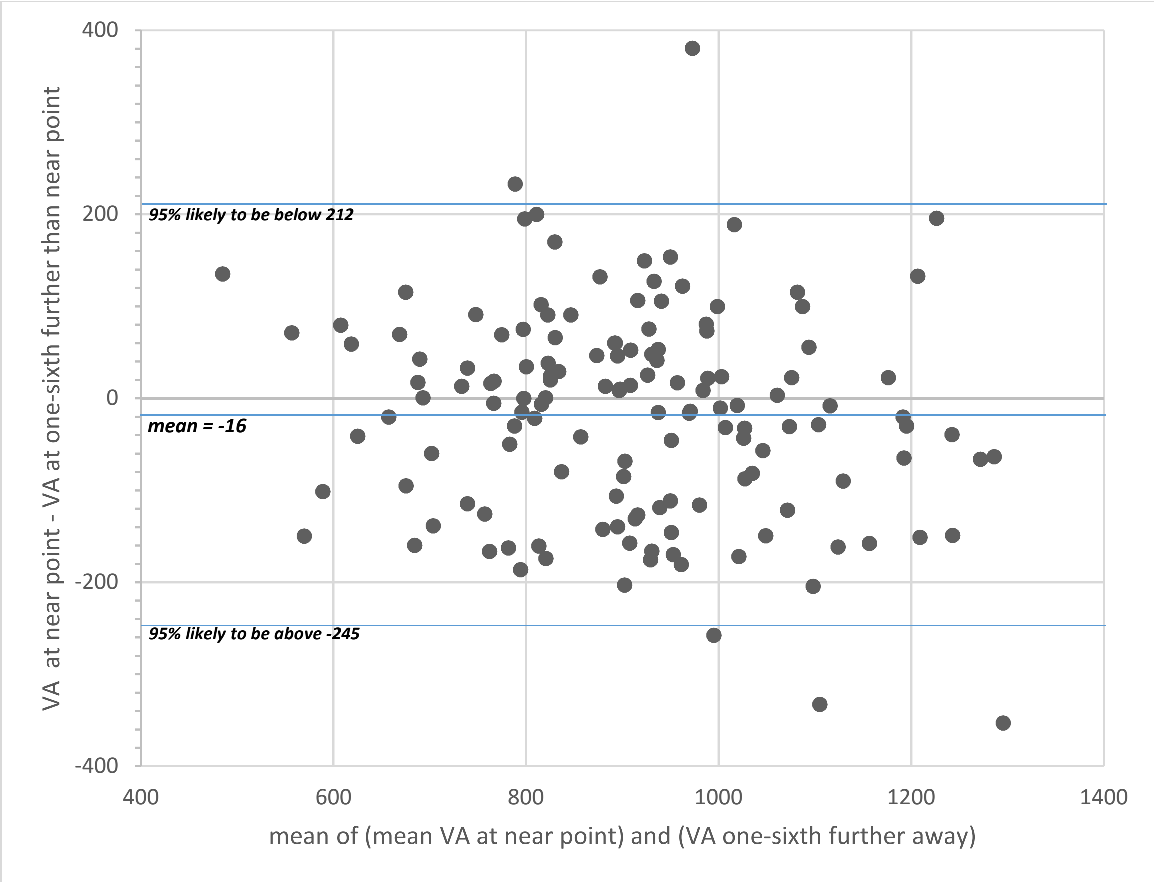

Figure 5.20 Difference plot of mean VA expressed as a cotangent, in Session 1 with the TRU at the near point and at one-sixth further away than the initial measurement (n = 142)

The BMPV(95%), as defined in Section 4.2, of VN was ±13.67%. Measurements tended to increase slightly when repeated, as mean measurements for all participants averaged 1.26% more in subsequent measurements. However, this increase was not statistically significant, as shown by ANOVA: each participant gave five measurements so there were four series of increments, for which a single-factor ANOVA showed (p = 0.261) no significant difference between the means of these four groups.

5.4.1 The effect of visual acuity at the near point on AoA measurement with the TRU

AoA decreases with age so the near point gradually becomes further away. Adaptation to that change may lag, so that the TRU may tend to be held nearer than the near point.

To test that hypothesis, the five measurements of VN and of AoA, made with the TRU in the Session 1, were re-analysed.

The difference of each measurement from the mean for that participant was taken, as a proportion of the mean. As there were 143 participants who completed the measurement session, there were 5 x 143 = 715 proportionate differences from each mean of five for VN, paired with 715 corresponding variations for AoA. These two data series were parametric (Kolmogorov-Smirnov and Shapiro-Wilk tests both $p > 0.2$) and paired-samples t-testing showed that their means did not differ significantly ($p = 1.00$) although their range differed slightly being 0.725 for AoA and 0.668 for VN.

VN and AoA showed negative correlation (Pearson $r = -0.539$). This demonstrated a moderate tendency for the TRU to give lower AoA results when smaller letters were read by an individual participant.

5.5 Conclusion of chapter

The main outcomes of the analysis of the method comparison are summarised in Tables 5.3. The outcomes should be considered with the analysis of each method's precision shown in Table 5.4.

Table 5.3 Summary of results, detailed in Chapter 5, of precision and comparison of methods of measuring AoA

	Autorefractor	RAF Rule	TRU
Agreement		6.36 D with TRU	
95% Limits of Agreement		5.19 D with autorefractor	3.01 D
Bias		2.10 D above TRU	
		2.19 D above autorefractor	0.30 D
Repeatability *95% Limits of Agreement*	1.58 D	5.62 D	3.38 D
BMPV(95%)	±7.14%	±15.29%	±11.93%
Reproducibility *- between sessions* *95% Limits of Agreement*		6.57 D	2.89 D
Coefficient of Variation		±10.80%	±6.69%
Reproducibility *- between investigators* *95% Limits of Agreement*		5.10 D	2.56 D
Coefficient of Variation		±8.43%	±5.41%

In the Table above, *Agreement* and *Bias* between the RAF Rule and the TRU are a weighted mean of both sessions' results, and the BMPV(95%) is defined in Section 4.2.

Table 5.4 95% confidence intervals of estimated limits of agreement, for repeatability and reproducibility of RAF and TRU

Measurement units are dioptres.

	Instrument	
	RAF rule	TRU
Repeatability		
SD of individuals' differences	1.40	0.85
estimated range of 95% of differences	5.62	3.38
n	143	143
hence t for 95% Confidence Interval	1.98	1.98
SE of Mean	0.47	0.28
hence Confidence Interval	0.93	0.56
hence, allowing for 95% Confidence Interval		
upper limit	**7.47**	**4.50**
lower limit	**3.76**	**2.27**
Reproducibility between sessions		
SD of individuals' differences	1.64	0.72
estimated range of 95% of differences	6.57	2.89
n	110	110
hence t for 95% Confidence Interval	1.98	1.98
SE of Mean	0.63	0.28
hence Confidence Interval	1.24	0.55
hence, allowing for 95% Confidence Interval		
upper limit	**9.05**	**3.90**
lower limit	**4.09**	**1.80**
Reproducibility between investigators		
SD of individuals' differences	1.28	0.64
estimated range of 95% of differences	5.10	2.55
n	111	111
hence t for 95% Confidence Interval	1.98	1.98
SE of Mean	0.48	0.24
hence Confidence Interval	0.96	0.48
hence, allowing for 95% Confidence Interval		
upper limit	**7.02**	**3.18**
lower limit	**3.51**	**1.59**

Besides method comparison, this chapter has reviewed the validity of the data, has presented results regarding whether AoA may be higher with a handheld stimulus to accommodation, and has presented results regarding the possible relationship between visual acuity at high levels of accommodation and results of AoA measurement.

The results presented in this chapter will be discussed in the following chapter.

Chapter 6 Discussion

6.1 Method comparison: summary of conclusions

Three methods of measuring AoA were studied. One was an established method, push-up using the RAF Rule, one was a novel method, the TRU, and the other was a reference method, an open-view autorefractor.

Comparing results with the RAF Rule and the TRU, for repeatability, reproducibility between sessions and between examiners, agreement and bias, the TRU was shown to be more accurate than the RAF Rule. The results were summarised in Table 5.3 and 5.4. They show that repeatability was better with the autorefractor than with the RAF Rule or with the TRU, that the TRU was a more precise instrument than the RAF Rule and gave results closer to those of the autorefractor as reference method. These differences between results with the RAF Rule and with the TRU would be of tangible clinical significance. They are now discussed and their implications for clinical practice and for research are considered.

6.1.1 Repeatability of methods

The repeatability of a method of measuring AoA was given as its BMPV(95%) (described in Section 4.2) and also as its estimated 95% limits of agreement.

Table 5.3 contrasts the BMPV(95%) of each method, drawn from the results in Section 5.2. The BMPV(95%) figures show that the TRU was 28% more repeatable than the RAF Rule. This may be an underestimate, for the following reasons.

- The RAF Rule requires identification of blur to identify the measurement end-point. It is likely that the participant would have remembered what the blur looked like. That criterion, an individual's subjective impression of the end-point blur, could then be recalled for the repeated measurement in the same session. However, the criterion may change over time and it would also probably differ for different observers.

- Furthermore, the experimental protocol used in this study changed the distance and visual object at which the TRU end-point occurred with every repeated measurement, removing a cue to replicating the measurement with the TRU but not with the RAF Rule.

Table 5.3 also shows that results with the autorefractor were substantially more repeatable than those with either test method. The estimates of the repeatability of each method may not be strictly comparable as the number of measurements per participant was different for each method, and that fewer participants completed autorefractor readings. Nevertheless it was encouraging to note that the clinical methods did not differ greatly in their repeatability which could be of a useful level for clinical practice, and that the autorefractor, intended as the reference method, appeared considerably more precise.

Table 5.3 showed that the 95% limits of repeatability covered a larger margin than the reproducibility, for both clinical methods - for the TRU for both types of reproducibility investigated, and for the RAF Rule's reproducibility between investigators. This was anomalous because repeatability is a part of all types of reproducibility so theoretically it cannot cause a greater variation in results than reproducibility. However, the confidence intervals shown in Table 5.4 show that this anomaly may be due to variation in results, such as due to sampling error.

That may not completely account for the anomaly, which could also be due to a combination of factors such as:
- possible inter-investigator difference
- random variation such as would be generated if AoA were not constant
- assessment of TRU repeatability being from the first and last measurements of a series of six in one session
- and a possible effect of the participant dropout between sessions.

On the other hand, repeatability of TRU measurement was 8.3% worse when its data excluded any obtained with dioptric adjustment, as for the other methods and for measurements in Session 2.

There is, however, no evidence that any of those factors contributed to the anomaly. Further investigation of this anomaly would be appropriate if the clinical significance of these effects were quantified. Measurement of AoA can show some statistically significant effects but, as Chapter 2 shows, their clinical significance is at present not always clear.

The mean results of repeated measurement in this study did not suggest fatigue of accommodation or any learning effect. Results were on average slightly lower in

Session 2 but no measurement method showed notable change except, as shown in Section 5.2.4, the RAF Rule showed mildly but significantly higher readings at the end of Session 1 than at the start. This could have been due to fatigue of attention.

6.1.2 Comparison of results with the RAF Rule to those with the TRU

Section 5.3 shows that agreement between results with the RAF Rule and those with the TRU was weak. In Session 1 the average mean RAF Rule result was 35% higher than for the TRU. Session 2, with fewer measurements of fewer participants, gave a similar discrepancy, 32%, which was slightly lower, 30%, when including the secondary investigator's results, possibly suggesting bias as discussed in Section 2.4.5 (though that effect appears slight) as the primary investigator had more motive than the secondary investigator to favour the TRU over the RAF Rule.

The lack of agreement between the two methods' results is shown by the estimated 95% confidence limits of agreement between the methods, which were large. They were ±3.61D in Session 1 and ±2.50D in Session 2. This lack of agreement could be attributed to the sources of error in current clinical methods of measuring AoA. Section 2.4 lists 24 separate sources of error (if, to simplify, all of the sources of error inherent in retinoscopy as described in Section 2.4.6 are counted as one). Table 2.1 contrasts the two methods' sources of error. Few would appear to affect the TRU, whilst many more would be inherent in the RAF Rule and they tend to be individually sources of potentially larger error.

The repeatability of the two methods within a session was assessed by the same investigator repeating the measurement under the same conditions about fifteen minutes later. Participants may have felt that the conditions changed, as they wore a trial frame for the second measurement only, but that was unlikely to influence the results significantly and the summaries of results, in Tables 5.3 and 5.4, do not show considerable systematic change. Intrasession and intersession mean changes with either method were negligible compared to repeatability.

This demonstrated no fatigue or improvement of AoA, and that finding was supported by the autorefractor measurements. The mean change from the first to the third autorefractor reading was only about one-tenth of the mean of all the changes to a participant's next reading, and showed no prevalent direction.

The results for repeatability of the two test methods are given in Sections 5.2.1 for the RAF Rule and Section 5.2.2 for the TRU. Figures from Tables 5.3 and 5.4 show that results with the RAF Rule were less repeatable than those with the TRU, even after allowing for RAF Rule measurements being higher as discussed above. The 95% confidence limits divided by the mean AoA were, for the TRU, 81.6% of those obtained with the RAF Rule.

The results for reproducibility between sessions are given in Section 5.3.1. In that Section, data from Table 5.2 and the confidence limits displayed in Figures 5.10 and 5.11 show that the TRU was substantially more reproducible than the RAF Rule between sessions, even when allowing for RAF Rule measurements being higher (as shown in Section 5.3). For example, the 95% confidence limits divided by the mean AoA for the TRU were 59.6% of those obtained with the RAF Rule.

Agreement between the two investigators' measurements with both methods is shown in Figure 5.12 for the RAF Rule and Figure 5.13 for the TRU, the latter showing the closer agreement. That was also evident statistically as the 95% confidence limits divided by the mean AoA were, for the TRU, 65.6% of those obtained with the RAF Rule. The lack of agreement could be attributed, at least in part, to the methods' relatively large repeatability described in this Section. No relationship was found between inter-investigator difference and any other measurement.

The mean results comparing inter-investigator reproducibility, given in Section 5.3.2, were compared by paired t-testing. This showed no significant difference ($p = 0.882$) between the two investigators' means when using the TRU, but a significant difference when using the RAF Rule ($p = 0.041$). Furthermore, there was better correlation between the two investigators' results for the TRU (Pearson's $r = 0.962$) than for the RAF Rule (0.899).

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A difference between the two sessions' results is shown in Figures 5.6 and 5.7. Although both sets of data showed prominent slope (reflecting the relatively higher readings by the RAF Rule at higher mean values of AoA) the slope was greater in the Session 1. As shown in Figures 5.6 and 5.7, the first-degree regression line fitted by Microsoft Excel to the data had a gradient of -0.48 in Session 1 and -0.34 in Session 2.

This mild difference, between the outcomes of the two sessions' comparison of TRU and RAF Rule results, may have arisen partly from the differing derivation of each participant's mean data in the two sessions. In the first, they were the mean of five TRU measurements and two RAF Rule measurements, all by the principal investigator, whereas in Session 2 the principal investigator and a secondary investigator each performed each method once.

6.1.3 Comparison of results with the RAF Rule, and of those with the TRU, to results with the autorefractor

In Section 5.3.3, results with the RAF Rule and, separately, results with the TRU were compared to those with the autorefractor. This was an indirect comparison of the two methods. Their direct comparison was discussed in Section 6.1.2. The direct and indirect comparisons agreed quite closely.

The autorefractor agreed well with the TRU but less well with the RAF Rule. Estimated 95% limits of agreement with the autorefractor were ±1.50D for the TRU but ±2.59D for the RAF Rule. The difference, divided by their mean, between measurements with the autorefractor and each test-method, was 12.6% for the TRU but 33.7% for the RAF Rule.

The autorefractor gave a lower mean result than the TRU for 73.1% of participants but lower than the RAF Rule for 94.2% of participants. This was more evident at higher levels of AoA, as shown in Figure 5.17, where major sources of error with the RAF Rule, such as depth of focus and reaction time, become greater as explained in Sections 2.4.1 and 2.4.2.

Section 3.6 includes discussion of previous work showing the autorefractor's trueness for AoA measurement, finding that the trueness was uncertain. Nonetheless, the autorefractor may provide a useful reference index of AoA, as may the TRU, considering their agreement shown in Figure 5.18.

6.1.4 Summary of method comparison

Push-up using the RAF Rule, the standard and prevalent method of measuring AoA, was found to lack trueness compared to a novel method (the TRU) and to a reference method (the autorefractor). Agreement was substantially stronger between the autorefractor and the TRU than the RAF Rule. The main factor in the inaccuracy of the standard method was its varying and largely inconsistent bias to elevated results. Its repeatability was quite close to that of the novel method.

The RAF Rule appeared to give moderately less repeatable results than the TRU when repeatability was specified by BMPV(95%). However, its variability may in reality be worse, as explained in Section 6.1.1. Similar disparity between the two test methods' precision was also shown by comparing their repeatability using unadjusted technique just at the start and end of the session (Figures 5.3 and 5.4) reproducibility between sessions (Figures 5.10 and 5.11) and reproducibility between investigators (Figures 5.12 and 5.13).

Overall, these results demonstrated that measurement of AoA was more reliable with the TRU than it was with the RAF Rule push-up method. The effect appeared to be of sufficient magnitude to support the experimental hypothesis given in Section 1.5.

6.2 Comparison with previous work

No previous work was found directly comparing any of the three methods of measuring AoA compared by this research. However, the findings of this research are in agreement with previous research described in Chapter 2 (Anderson and Stuebing, 2014) showing that autorefraction gave substantially lower results for AoA than were produced by push-up.

As discussed in Chapter 2, where research has compared results with the push-up method and any other method, such as reports by Hamasaki *et al.* (1956), Sun *et al.,* (1988), Rosenfield and Cohen (1996) and Antona *et al.* (2009), it has not shown results with the push-up method to be more reliable than those obtained with another method. This study would support that finding.

The theoretical and empirical reports, described in Section 2.4.6, that proximal effects increase AoA, were not supported by this study. The results in Section 5.3.4 showed a general slight decrease in AoA when the participant was made more aware of the target's nearness and controlled it.

This study is the first for approximately a century to introduce a completely new method of measurement of AoA. The limitations of the predominant method (RAF rule) are highlighted and it shown to have poor repeatability and reproducibility. A new method (TRU) is introduced and is shown to have better repeatability and reproducibility than the RAF rule.

6.3 The size of TRU characters

The TRU was designed to present a range of character-sizes. The extent of this range, and the size of each step in the range, could both influence the instrument's efficiency. These parameters had not been empirically optimised before this study. They could influence the TRU's accuracy, as follows.

The range should be large enough to include some letters legible by any individual for whom AoA would be measured (with distance refractive error corrected but no other visual aid in place). No relevant published reports were found of the limit of resolution with extreme accommodation. As explained in Section 2.3.1.1, that limit may differ from distance visual acuity. The results in Section 5.4 would support that contention as they show that visual acuity at and near the near point is significantly less predictable than geometric optics would suggest.

Larger step size would reduce repeatability of measurement. It should not be large enough to materially reduce it.

A larger range, or smaller steps, than these considerations require would increase the number of letters. That would make the device slower and more tedious to use, and consequently less accurate for people, such as children, who are easily distracted, possibly reducing its value in clinical work and in surveys of AoA.

Considering the range of letter sizes, larger letters appeared to give participants confidence and understanding of the visual task, while according to the Threshold Resolution principle (Section 3.3) the smallest letters resolvable are the optimal stimulus for the accurate measurement of accommodation. Some TRU letters were substantially smaller than any that can currently be displayed on any consumer-electronics screen (so they were produced by photography) or than any in peer-reviewed publications of AoA measurement. The smallest were about one-fifteenth of the height of the letters used in this study on the RAF Rule (and labelled "N5" but shown by the measuring microscope to be about 25% larger than N5 but of low quality printing as shown in Figure 1.4). Piloting the TRU revealed that nobody without at least 3D of myopia could read a few letters above the smallest.

In this study, 88% of the participants could read some letters in the column of smallest letters on the TRU, and all of the participants could read some letters in the adjacent column. The smallest letter that was read by any participant was 0.0923 mm high while, as stated in Section 3.5, the smallest letter displayed by the TRU was 0.075 mm high.

Therefore the range of character-sizes displayed by the TRU appeared to have been a little larger than was required for this study. Removing the column of largest letters and the two or three smallest letters may slightly improve the TRU's efficiency. However, in clinical work lower visual acuities are encountered than were included in this study. If the TRU were in routine clinical use it should cater for low normal visual performance. Section 3.5 explains the basis on which the size range of the letters on the TRU was set.

On repeating TRU measurement under repeatability conditions, the average change was 11% and the proportionate change was distributed normally (Kolmogorov-Smirnov test $p > 0.2$). Set against that, the step size of 5% would appear small enough, with only about a quarter of repeated measures being influenced by step size.

Step size could even be a little larger, perhaps up to 7%, to streamline the clinical application of the device. Furthermore, at the near point many participants read a letter incorrectly but then the next smaller one correctly, suggesting that the steps were too gradual. On the other hand, the gradual progression also appeared to help give participants confidence in reading the smallest letters.

Overall, based on the data obtained and on the experimenter's subjective experience in using the TRU, the design of the instrument was found to be adequate for the purposes of this research. Furthermore, this study has shown that it could be simplified a little to optimise it for clinical use. This optimisation would be based on factors including VN, the visual acuity at the near point. It would be helpful to know the population mean and standard deviation of VN in redesigning the TRU and perhaps in the design of handheld display devices in general.

6.4 The possible value of counting TRU letters in measuring AoA

In Section 4.5.1 the measurement of VN was proposed as a possible reinforcement of AoA measurement with the TRU. However, VN may not be useful in this context because of uncertainty, described below, in its measurement.

As mentioned in Section 5.2.2, the results for minimum height of discernible TRU letters correctly read at the near point did not resemble a normal distribution ($P < 0.0005$ by the Kolmogorov-Smirnov test). Nonetheless, as the BMPV(95%) of TRU results for AoA, 11.93%, was close to the 12% figure obtained for letter-resolution, this method's imprecision might be attributable to variation in visual acuity.

The results for minimum height of discernible letters at approximately one metre in the preliminary investigation were distributed normally (Shapiro-Wilk test $p = 0.57$) and showed better repeatability, with a BMPV(95%) of ±6.30% compared to ±12.00% at the near point as mentioned above. At this longer testing distance there was a 5% chance that a single reading would differ from a repeat of it by at least 1.89 letters and there was less variability in TRU results for VA (BMPV(95%) = ±5.41%) than at the near point.

The worse repeatability at the near point could have been because the near point task, compared to reading the TRU beyond the near point, may have been psychologically more stressful, would have required more steadiness in holding the unit, and may have been influenced by possible variations in AoA (although such variation would have been smallish, as the autorefractor's BMPV(95%) of ±7.14% suggested).

The possibility of idiosyncratic variation in VA with viewing distance cannot be excluded. Johnson (1976) reviewed previous publications that had examined that possible relationship and concluded that viewing distance had no effect on VA. However, the papers that he cited in support of that contention offered quite uncertain evidence for it. Heron *et al.* (1995) compared visual acuity at different distances , finding no overall trend other than reduction at the shortest viewing distances; which may reflect, as their data suggested, that some or all of their participants had insufficient accommodation. Buehren and Collins (2006) measured VA at a range of accommodative demands up to 5D and found that VA was about 30% better at low than at high accommodation but this was for only ten participants and experimental conditions that were quite unnatural. No other relevant reports of variation in VA with viewing distance were found.

Furthermore, in comparison of TRU results for the first and last measurement conditions in Session 1, measurements of near-point distance were very closely matched as shown in Section 5.2.4 whereas measurements of acuity were not. The mean VN in the first condition was 876 and 920 in the last, and a paired-samples t-test showed a significant difference between the means ($p = 0.0005$).

Moreover, the findings shown in Section 5.2.2 suggest that the TRU letter-counting data were unreliable compared to the TRU distance-measurement data (even though the distance-measurement might seem inaccurate due to factors including parallax detailed in Section 4.2.1). This comparison suggested that letter-counting would not contribute reliably to the measurement of AoA. That was attributable to variation in an individual's visual acuity at the near point. VN may be an unreliable guide to AoA also because of the variation in legibility between test-chart characters, the inherent variability of any biological sensory threshold, and the uncertain accuracy of the extreme accommodative response.

Counting letters of decreasing size may assist in measuring AoA as it gives the clinic patient or research participant a clearer index of achievement that reinforces effort, as described in Section 2.4.7, more effectively than in any other method of measurement.

6.5 The likely maximum AoA

As shown in Table 2.2, studies of AoA have covered a range of age from early childhood to beyond the descent into presbyopia. They gave maximum AoA occurring at different ages, perhaps because the lowest participant-age varied while the studies generally showed continual decrease with age. The age of maximum AoA is therefore unclear. Accommodation allows children in a hunter-gatherer group to learn fine near-vision survival tasks described in Section 1.2.2.4, so AoA might be expected to be maximal at an age when the child can begin to learn those tasks and to remain maximal for a few years allowing the honing of skill in those tasks.

Maxima of AoA, found by studies of it, have covered a notably large range. The extremes of the range are represented by results such as those of Kaufman (1894) and Adler *et al.* (2013) showing maxima more than double those found (at similar ages of participants) by Anderson and Stuebing (2014) and Leon (2016). The extent of this range, from about 8 D to over 20 D, can be attributed to differences in methodology, as discussed in Section 2.6 which also showed that, at any age, lower values of AoA generally arose in studies using apparently more accurate measurement methods.

There are other reasons to take the lower values as more credible than the higher values. Consider the advantages and disadvantages of high accommodation. The only advantage would be to see smaller objects. How useful would that be? Suppose that in favourable but ordinary viewing conditions such as daylight, a healthy eye with normal visual acuity views a dot that has high contrast to its background. Under these conditions the eye can resolve the dot if the dot subtends slightly less than one minute of arc at the eye. An eye with such resolving power, accommodating at levels around 15 D as reported in the surveys of AoA most commonly cited as detailed in Section 2.6, would be able to resolve detail smaller than some human epidermal cells (if visual acuity does not decrease much at the near point). In an evolutionary context, the survival value of such fine resolution appears unclear.

High AoA may prolong the decline of AoA and would maintain sharp sight in ageing hypermetropes, but those effects are conjectural and marginal. To this author's knowledge, evidence of the survival value of higher AoA, or lack of it, for humans in air, has not been published, though higher AoA is an advantage for people who find food underwater as shown by Gislen *et al.* (2003).
The possible benefit of high AoA can be set against the following five factors suggesting the absence of such benefit.

- Binocularity, with its benefits of depth perception and increased acuity compared to monocular viewing, would become stressed due to the high levels of convergence required by the extremely short working distance required for sharp sight at high accommodation.
- Binocularity would become more unstable when viewing an object directly in front of one eye at shorter viewing distances resulting from higher AoA due to increased difference between the two eyes' retinal image size.
- Relaxing accommodation and convergence for clear distance vision might be expected to take longer from higher accommodation levels, so that would be a survival risk.
- The eye's optical performance would be expected to have evolved as optimal for most frequent viewing distances.
- Higher AoA may weaken other ocular functions. This is because accommodation is a mechanical change. High AoA would increase the possibility of this mechanical system's operation interfering with the function of adjacent structures in the small physical space within which it operates. For example, higher AoA requires greater movement of the ciliary muscle and possibly greater blood supply to it. The resulting mechanical stress, due to the muscle's greater shifting, engorgement and disengorgement, might influence the adjacent production and drainage of aqueous humour.

These five factors suggest that the evolutionary selection of high AoA has been unlikely. AoA was simply adequate for the lifespan. During the aeons in which the current human genome evolved, most people died without becoming presbyopic.

The last three of the five factors listed above would support the contention that evolutionary advantage may have been gained from a decrease in AoA with age. The moderate decrease in AoA during early adulthood, as shown by the surveys mentioned in Table 2.2, would cause no significant problem to the hunter-gatherer individual growing to maturity with the attainment of toughness, longer arms, and responsibility for distance visual tasks (as also described in Section 1.2.1.4).

Presbyopia, which is Latin for Old Age Eyesight, probably became associated with senescence when it was first recognised because, as discussed in Section 1.2.1.4, it generally arrived when individuals were well past their prime. However, the association of presbyopia with senescence may be incorrect. While average years of other aspects of physical fitness have, in general, extended substantially, but those of accommodation have not. There is no evidence that presbyopia arrives later than when measurements of it were first published which was by Donders (1864). This suggests that the decrease in AoA with age is not involutional. Work by Pierscionek and Weale (1995) considered normal lifelong biological changes (such as lens growth) that may reduce AoA with age. They showed that the decrease of AoA with age is a type of change that is not principally of senescence, as commonly assumed, but of non-involutional factors. They pointed out that all surveys of AoA with age had shown that, on the whole, AoA decreased before changes related to senescence began. This remains true.

In conclusion, normative surveys showing lower values of AoA may be considered as more credible. Furthermore, the decrease of AoA with age may be considered as a multifactorial function, primarily of growth, and therefore one might expect age-norms to be more complex than the reliable first-order relationship sought (unreasonably and unsuccessfully) as described in Section 1.3.3.

6.6 Strengths and limitations

Two strengths and five limitations of this study are presented below. They are in approximate order of decreasing strengths followed by increasing limitations.

6.6.1 Masking of measurement

Participants could not express measurement bias because they did not know the measurements. Even when the same investigator carried out the measurements at Session 2, these were done without any guide to the previous result or memory of any particular measurement. Therefore, the study might be described as double-masked although the principal investigator took measurements at both sessions.

6.6.2 Measurements of accommodation other than its amplitude

Although AoA is the principal parameter of accommodation, as Section 2.1 describes, it is not the only accommodation-parameter of clinical or research interest. Others are discussed below.

Accommodation intrinsically fluctuates as mentioned in Section 1.2.1.1. The amplitude of these fluctuations was not taken into account in this study but would have slightly inflated measurements made with the autorefractor and the TRU. The extent of that inflation is unclear. Charman and Heron (2015) reported that the amplitude of the fluctuations had been found to vary with parameters of the visual task, being reduced for higher-contrast visual objects (as were used in this study) but increased for more finely-detailed visual objects (also such as used in this study) while the level of accommodation would have exerted an uncertain effect and other effects from parameters such as pupil diameter, as pupils constrict with accommodation (Marg and Morgan, 1949) further confound estimation of the inflation.

The fluctuations would account for at least some of the variation, without clear pattern, in successive autorefractor measurements. Figure 5.16 illustrates the variation It also shows some irregular gaps in the otherwise quite regular pattern of measurements that unfortunately tended to occur at high levels of accommodation and may have been due to slight head-movement, especially near the end-point of measurement because the extreme accommodation sought in this study constricted some participants' pupils to the minimum diameter at which the instrument can measure refraction, while measurement was likely to become less reliable as the instrument was designed and validated for the unaccommodated eye which has substantially different optical properties to those of the accommodated eye as explained in Section 2.3.1.1.

In investigating AoA, the predominant means of assessing accommodation, the thesis does not consider other clinical means of assessing accommodation such as

- accommodative response, which is the relationship between the level of accommodative demand and the degree of accommodation resulting

- accommodative facility, which is the speed of response to regular fast repetitive changes in accommodative demand

- the relationship between accommodation and related functions such as convergence, mentioned in Section 1.2.1

- blur point, which is a measure of the flexibility of the relationship between convergence and accommodation

- measurement of pseudoaccommodation, which is the extension of the eye's dioptric range of focussing by tolerance of reduced image quality.

6.6.3 Data congruence

The number of days between Session 1 and Session 2 for each participant was analysed in Section 5.1, showing a large and uneven spread of the length of the interval between sessions. Section 5.3.1 shows that this variation had no statistically significant effect on the results.

Gender of participants was quite well balanced. In any case it was not expected to influence AoA given the conclusions of meta-analysis by Hickenbotham *et al.* (2012).

The comparison of method-precision may have been influenced, statistically, by the differing numbers of measurements with each method and also empirically by the differing numbers of participants for each method. Section 5.1 shows that the 23% of participants who completed Session 1 but did not return for Session 2 were not strongly representative of the whole participant group, in that their AoA tended to be lower though the difference between the two groups' means was, statistically, only weakly significant. It is not known how their inclusion in Session 2 might have influenced results.

Section 5.1 also shows that the 16% of participants for whom the autorefractor could not provide three readings under the same measurement conditions had shown substantially higher AoA. No explanation was found for this. It may be an issue to explore if piloting further research into extreme accommodation using similar equipment.

Section 6.1.1 mentions that the experiment's methodology would have been more likely to have led the participant to expect end-point distance to change for the TRU than for the RAF Rule. This may have led to overestimation of the RAF Rule's repeatability.

6.6.4 Possible sources of variation and error in measurement of AoA with the TRU

This study reports many peer-reviewed publications including critical appraisal of measurement of AoA with the RAF Rule. It cannot balance that with reports of TRU use because there are no other reports of it.

Such reports might assess the following possible weaknesses of the TRU. The results in Section 5.4.1 imply a tendency to hold the TRU slightly closer than the near point, reducing trueness in measuring AoA with the TRU. Furthermore, validation of the measurement method used with the TRU could be more thorough, as detailed in Section 4.2.1. Revision of the technique of TRU use (see Section 6.7.1.1) could address these possible source of error.

Variation in TRU results for an individual could also be due to the possible variation in AoA over any timescale (discussed in Section 6.6.6) and may cause any method of measurement of AoA to give varying results. Graduation of letter height, as discussed in Section 6.3, adds some imprecision but it would be less than the step change in height of subsequent letters in the TRU, which in this study was 5% as described in Section 3.5. Other possible sources of imprecision may include the patient's level of motivation and of hand tremor.

6.6.5 Bias

As mentioned in Section 3.2, the TRU was designed, constructed, and prototyped in routine clinical practice by the principal investigator. This involvement with the development of a technique may have been a source of bias for the principal investigator throughout this research. Measures to minimise investigator bias included the quantitative stance of the study, use of the secondary investigator, and the use of masking.

6.6.6 Possible short-term variation in AoA

An individual's AoA may vary from moment to moment. It is powered by a muscle as described in Section 1.2. The peak effect of muscles is not very predictable, as any athlete can attest. Variation may also arise from changes in the physical properties of other parts of the eye wherein the deformability of tissues affecting accommodation may vary with other unpredictable changes such as levels of perfusion and hydration.

The possible variation of AoA is a source of unknown inaccuracy in non-simultaneous method-comparison for measuring AoA. No research into this possibility was found. In this study, the variation may be shown by the change on repeated measurement of each participant's AoA with each method though it could also represent imperfect repeatability of any measurement method. It may influence the momentary and longer-term fluctuation seen in the results with the autorefractor.

There is also the possibility of adaptive change in the power of the mechanical system driving accommodation causing variation in AoA, but no research into that isolated contention was found. The results of repeated measurement of AoA in this study (see Section 5.2) do not show any significant systematic reduction. Work by Vilupuru *et al.* (2005) and Wolffsohn *et al.* (2011) suggests that accommodation is not fatigued by such repeated experimental measurement.

There is no literature support for the contention that accommodative power is changed by accommodative effort, as either a fatigue effect or as a training effect. A PubMed search in February 2017 for "smooth muscle" and "fatigue" in titles and abstracts showed only three reports (simply measuring the contractile force of non-hominid bladder muscle strips in vitro, and demonstrating great muscle-fatigue) but replacing "smooth" with "ciliary" in the search terms gave no relevant results.

6.6.7 Validity of the reference method

Literature reviewed in Section 3.6 suggests that the autorefractor used in this study was of uncertain validity for measuring accommodation. However, it is reassuring that in the present study the lag of accommodative response to demand was only about 5%, being a relatively flat deficit averaging 0.3D. This improvement in the autorefractor's apparent trueness, shown in Figure 5.18, was with the TRU. Possible reasons for the different apparent trueness when using the TRU include the following: this was method comparison, the accommodative stimulus was finer detail, measurement with the autorefractor was at the near point, and was performed after TRU measurement.

Outside this present study, the principal investigator made a series of small investigations summarised in Appendix 9 exploring the accommodative response measured by the WAM-5500 to accommodative stimuli presented by the TRU, finding that the mean response was an apparent accommodative lag of 82% of the stimulus. The lag varied moderately between participants and with stimulus level but with no clear relation to stimulus level. This supported the inference of data from the studies reviewed in Section 3.6 as mentioned above*,* that the WAM-5500, as a guide to accommodation, has not demonstrated trueness.

The instrument's producers were aware (Grand Seiko, 2007) that the WAM-5500 measured a lower value of accommodation than the user would expect. Instructions supplied with the instrument stated that the eye under-accommodated by 0.75 D irrespective of the level of accommodative demand. Evidence for that claim is unknown.

Research with other instruments measuring accommodation objectively is not addressed here in detail, if only because the instruments were somewhat different to the WAM-5500 used in this study (such as in minimum pupil size, available functions, footprint, and shape of infrared object) even if appearing similar. An example is the study using the immediate predecessor of the WAM-5500, by Whatham *et al*. (2009) showing a similar disparity to that found with the WAM-5500 between accommodative stimulus and apparent response. Other examples of autorefractors that gave similar disparity were reported by Win-Hall *et al*. (2010).

Overall, the research that would validate the WAM-5500 generally found less parity, between accommodative demand and the measurement of accommodation, than the 82% quoted above, and largely did not report measurement at or near maximum levels of accommodation. The disparity appeared larger in research with the WAM-5500 than in other research with its predecessor, the Grand Seiko WR 5100K. None of the authors who found this trueness-deficit appears to have considered the possibility that it might show inaccuracy in the autorefractor, or show anything other than “accommodative lag” or suggest the assessment of a second sample of the same instrument.

Validation of the WAM-5500 as a method for measuring AoA could, therefore, receive further attention. However, even if its trueness is uncertain, an instrument may nonetheless be valid for indirectly comparing test methods, as in this study, if other aspects of its reliability, such as precision, are better than those of the test methods, and that contention is examined next.

Win-Hall *et al.* (2007) suggested caution in viewing reports of validation of infrared-beam autorefractors for measuring accommodation, because the optics of the accommodated eye differ from those for which the instrument was calibrated. In extreme accommodation the eye may make the image of the instrument’s infra-red object assessed by the instrument’s photodetectors smaller enough to affect measurement significantly.

Win-Hall *et al.* (2007 and 2010) also suspected that reflections, of an autorefractor’s measurement beam from the surface of trial lenses, tended to disturb the instrument’s measurements, as did Kimura *et al.* (2007) Glasser (2008) Atchison and Varnas (2017) and the present author.

Kimura et al. (2007) empirically, and Atchison and Varnas (2017) using theoretical considerations, evaluated another possible source of error with the use of autorefractors to measure accommodation, arising from the reference position of added spectacle lenses’ power in viewing a near target. They showed that correcting for that geometric-optics error source is not straightforward. and that the errors, which would be of the added lenses’ effectivity, would not be high enough to change the conclusions of this study (and would have tended to inflate autorefractor measurements). Other workers, including Anderson and Stuebing (2008) and Anderson *et al* (2014) made a correction for that source of error.

Notwithstanding these known and suspected sources of error, the instrument may anyway be measuring a function closely related to accommodation but differing from it as suggested in Section 2.3.1.1. Furthermore, as described in Section 5.1, for more than a third of participants the instrument could not provide the few measurements required for the fully accommodated eye, and those participants tended to demonstrate substantially higher AoA, with the RAF Rule and with the TRU, than the other participants. This inconsistency may not be acceptable in a reference method.

Overall, the published validation of the WAM-5500 for measuring accommodation does not support its use for this purpose. Methodological considerations, such as accommodation levels studied, could account for the lack of validation. This lack of validation may be more relevant at extreme accommodation levels as investigated in this study.
Given these findings, the reference method of measuring AoA in this study is considered by the author to be questionable, although the literature shows that it is widely accepted as a gold standard. The WAM-5500 has not been shown to provide anything other than an unsystematically approximate, and low, index of accommodation, albeit with good repeatability as described in Section 5.2.3. It is a major limitation of any investigation into methods of measuring AoA that no reference method of measurement of AoA has been shown to be reliable.

The validity of the reference measurements in this study may be further limited by the low number of readings obtained for each participant. The autorefractor was used to measure each participant's AoA four times or less (and three of the measurements were carried out in one manner but the fourth was in another manner, hand-held). This factor would reduce the precision of the autorefractor findings. The above-mentioned research by Win-Hall *et al.* and by Kundart *et al.* was similar in this respect, while that by Aldaba *et al.* was based on ten measurements per participant.

6.7 Suggestions for Further Work

6.7.1 Empirical investigations to improve clinical measurement of AoA

6.7.1.1 Using the TRU

During use of the TRU the author noted that, for measurement, it usually seemed to be held immediately at the near-point, so that adjusting the visual working distance did not allow the resolution of smaller letters than the smallest that were correctly read initially. This tendency was not confirmed by measurement but, if confirmed empirically, would suggest intuitive knowledge of the near point, tempered by the possible slight tendency to optimism mentioned in Section 6.6.5 wherein participants appeared to tend to hold the TRU slightly closer than the near point. Therefore further work could address agreement between the initial "intuitive" distance and the near-point distance as subsequently refined by alternative sets of instructions. Close agreement would simplify use of the TRU.

Proposed investigation such as the foregoing could also address the effect of different sets of instructions for the TRU and to compare their speed and simplicity with the use of the RAF Rule. Anecdotally, the TRU appears to be the quickest and easiest method of measuring AoA.

The accuracy of the measurement of the distance from the anterior pole of the eye to the TRU may be improved by automation. Further work could explore techniques for automating the measurement and comparing its results with those of the measurement technique used in this study as described in Section 4.3.1.2.

In a production version of the TRU, electronic lamps would replace the incandescent backlighting used in the prototype instrument investigated in this study. Electronic luminaires can be controlled for constant light output, facilitating further research assessment of the TRU. Setting the luminance contrast would simplify further research which would be of value if only because the novelty of this device, the current lack of reports of its use, and its application for routine eye-examination, call for comprehensive investigation of its performance.

6.7.1.2 Using methods other than the TRU

No studies were found of AoA measurement with a constant retinoscopy working distance such as 67cm measuring with lenses, as in ordinary clinical retinoscopy, while accommodation is maximally stimulated with a moveable target for the other eye. A long working-distance makes retinoscopy more precise, as mentioned in Section 2.4.3.4. It could be the basis of an accurate and objective method, may facilitate interocular comparison, and could be used under monocular or binocular conditions. A transparent and anti-reflection coated target, and attention to maintaining axial measurement, would be required.

Depth of focus, as discussed in Section 2.4.1, is a large source of error in AoA measurement. One novel approach to reducing errors due to depth of focus might be to use vanishing optotypes. These were described by Shah *et al.* (2011) who noted that they had been in use for more than thirty years and showed promise for wider application in clinical work. Vanishing optotypes have not appeared in literature concerning the measurement of accommodation.

6.7.2 Empirical investigations to improve reference measurement of AoA

As discussed in Section 6.6.7, the WAM-5500 autorefractor did not provide a valid reference-standard measurement. Further work would address its validation for this purpose, initially through expanding experiment (1) in Appendix 9, perhaps comparing the WAM-5500's results with a similar and with an alternative (validated, if available) objective system, simultaneously by using a beam-splitter or beam-chopper.

6.7.3 The possible standardisation of current clinical measurement

Setting normative values for a biometric parameter requires surveys that measure it using a standard procedure in sufficient numbers of well-specified subjects. The criterion for identifying abnormal values at a specified age may then be taken initially as the common biomedical default criterion which is that the 95% of values closest to the mean are considered normal (Gardner and Altman, 1989).

However, as shown in this review, the trueness of published norms of amplitude of accommodation is uncertain at present. Because of that, criteria for abnormal values currently cannot be identified with certainty and participant numbers for further normative studies cannot be predicted.

Ideally, a standardised, simple and accurate measurement method should be used in normative studies and the same standardised method should then be employed by clinicians so that their results can be directly related to the published norms.

It would be useful to eventually standardise the measurement of AoA but short-term standardisation to the push-up method could be attempted as follows:

- Limit the effect of depth of focus by using typical lighting for work requiring perception of fine detail, 500 Lux (HSE, 1997) and targets adjusted to the patient's acuity threshold at the target distance:
- Minimise reaction-time error by standardising target speed (rate of vergence change) to be constant, or by making step changes;
- Standardise the reference point for measurement (e.g., to corneal plane).

6.7.4 The quality of sight in high accommodation

This work has revealed a lack of published literature quantifying how finely a normal eye can see while accommodating to certain extents. Visual functioning at high levels of accommodation would be a suitable topic for further research. The behaviour of accommodation when maximum focusing effort is exerted during intense near-vision tasks such as smartphone use as described by Bababekova *et al,* (2011), fine inspection, or measurement with the TRU, should be investigated systematically, especially since autorefractor output in this study suggested that AoA varied; that accommodation did not show predictable behaviour when the target was nearer than the near point; that accommodation lagged considerably if that lag was not a measurement artefact; and that accommodation was not fatigued by repeated short extreme stimulation.

Focussing at high levels of accommodation may be analysed through inspection of the continuous output of the autorefractor synchronised with recorded movement of a fine visual target slightly within and beyond the near point. Target movement would be automated and programmed, building on the initial work by Drew (2013). The target would be interesting scrolling text such as a newsfeed, displayed on a high-contrast black on white screen and viewed binocularly. Letter-height would be continuously variable, from a minimum of about one-tenth of a millimetre, and could be linked to the target distance to provide constant subtense. Each participant's near point and minimum font size would be previously determined with this apparatus.

6.8 Conclusions

In the long history of measurement of AoA many authors have highlighted the limitations of the push-up method such as, for example, Jackson (1907), Berens and Fonda (1950) and Rosenfield and Cohen (1995). Still, as indicated in Section 2.3.2.1, the push-up method remains pre-eminent. This study set out to assess whether its pre-eminence appeared sustainable, by reviewing the literature and empirically, leading to the conclusion that the push-up method and its variants, as currently taught, should be used only selectively.

Community optometrists measure AoA, typically comparing their results with normal values derived from population surveys. AoA is commonly tested in children and the need for such testing in older patients will increase to, for example, manage visual strain and assess the performance of various methods of reinstating accommodation that refractive surgery and cataract procedures may provide.

Several methods are available to measure AoA and the strengths and weaknesses of each approach have been discussed, with comments on their precision and trueness. Suggestions have been made for standardising the clinical assessment of AoA, for further work to improve it, and for other related further work investigating the resolution of small high-contrast visual detail.

A simple novel instrument, the TRU, and the method with it for measuring AoA in routine clinical practice and in research, has been described and assessed. It was compared with the prevalent method and an objective instrument and found to perform satisfactorily, offering substantially improved accuracy. If user trials are successful, and particularly if further studies of the TRU method lead to improved clinical and research outcomes arising from its use, measurement of AoA should generally be performed with the TRU which should also be used to revise normative values.

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Appendix 1 Literature review by Burns *et al.* (2014)

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Clinical measurement of amplitude of accommodation: a review

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Introduction

Accommodation is the adjustment in the dioptric power of the eye to focus the retinal image of objects at a range of distances. Amplitude of accommodation (AoA) is the maximum increase in optical power that an eye can achieve in adjusting its focus from far to near. It has been measured in routine clinical eye examination for many decades (Rabbetts 2007). This paper will describe and appraise current methods of measuring AoA and make recommendations for standardising clinical methods. The validity of norms of AoA that are used in optometric practice will also be reviewed.

Why measure AoA?

> “With many of us the rule for measuring amplitudes is apt to gather dust in some corner of the test-room.” (Coates 1955).

Measurement of AoA is a recommended component of a routine clinical eye examination in the UK (College of Optometrists 2012a). The detection and management of common refractive conditions, including presbyopia and latent hypermetropia, are frequently assisted by determining AoA. The clinical relevance of AoA measurement will extend to evaluate the evolution of ‘accommodating’ intraocular lenses (IOLs).

Some pathological conditions and recreational and prescribed medications can infl uence accommodation. This can be detected through the measurement of AoA in routine clinical practice.

A wide range of physiological and other factors have been reported to infl uence AoA. They include refractive error (McBrien and Millodot 1986), ethnicity or race (Edwards et al. 1993; Kragha 1986; Rambo and Sangal 1960), adaptation to sunlight (Coates 1955), urbanisation (Eames 1961), periocular temperature (Takahashi et al. 2005), dyslexia (Evans et al. 1994) and other reading diffi culties (Palomo-Alvarez and Puell 2008), schoolchildren's visual and ocular comfort (Sterner et al. 2006), intraocular pressure (Dusek et al. 2012), diabetes (Moss et al. 1987), Down syndrome (Woodhouse et al. 1993), thyroid dysfunction (Cogan 1937), alcohol consumption (Campbell et al. 2001), premature birth (Larsson et al. 2012), time of day (Somers and Ford 1983), systemic medication (Rennie 1993) and visual axis declination (Ripple 1952).

The significance of these factors is difficult to determine because of limitations in the accuracy of the measurement of AoA, as discussed below. Improvements, including standardisation of measurement, are required in order to update normative values.

The increased use of small display screen devices such as smartphones is associated with higher levels of accommodation than conventional near-vision tasks (Bababekova et al. 2011). Analysis of visual efficiency for such work would require precise measurement of AoA because the visual task may require maximal levels of accommodation.

Methods of measurement

There are five methods of routine clinical measurement of AoA (push-up, push-down, push-down to recognition, minus lens, dynamic retinoscopy), with four of these being completely subjective. Retinoscopy is partly objective as it relies only on the clinician's interpretation of the reflex. Fully objective clinical measurement is possible, using an open-view autorefractor, but they are not yet widely used in optometric practice and are pupil size-dependent (Winn et al. 1989).

A search of the literature showed no systematic survey of current routine clinical practice in the method of measuring AoA. However, in standardised patient research (Shah et al. 2008) accommodation was measured by only 36 of 100 randomly selected optometrists examining a pre-presbyopic patient in routine clinical practice. The method was usually push-up and occasionally push-down or a combination of the two (Shah, 2013, personal communication).

Push-up

The push-up method is ubiquitous (Somers and Ford 1983): the 'commonest and simplest clinical technique to measure amplitude of accommodation' (Atchison et al. 1994). In this method the patient, optically corrected for distance vision, views a detailed test object approaching the eye and reports when there is 'the first slight, sustained blur' (Rosenfield 2009). The test object is then said to be at the eye's near point and its distance to the eye is measured. The measurement (in metres) is converted to its reciprocal to provide the AoA in dioptres.

This method, often using an instrument known as the RAF rule (Figure 1), is well established in clinical practice and research. However, it has several sources of error (Table 1).

Figure 1. The RAF rule.

Push-down

This method can be considered as a variation on the push-up method. In its initial description (Turner 1958), the test object is moved away from the eye until the patient reports when it first becomes clear. Rosenfield (2009) and Barratt (2013) have recommended averaging its results with the push-up method.

Push-down to recognition

This is similar to the push-down method except that the end-point is when the patient first recognises a target as it is moved away from the eye. It has been termed the 'modified push-up method' (Scheiman and Wick 1994), but that term has not been widely used. This method is currently promoted (eg Barratt 2013) and has been used in research (Chen and O'Leary 1998, Koslowe et al. 2010, Taub and Shallo-Hoffman 2012).

This method would be simpler for the patient because it requires the resolution of an object which may be easier than discerning clarity. The three methods so far described can all be measured under monocular and binocular conditions.

Minus lens

In this method (Sheard 1920, 1957) negative spherical lenses are added to the distance refractive correction until the subject cannot maintain the initial acuity at a preset viewing distance. The AoA is given by the maximum negative lens power added while the patient can maintain focus. This method, which is facilitated by using a refractor head (phoropter), should only be used under monocular conditions because it results in an excess of accommodative convergence which would be likely to disrupt binocularity.

Dynamic retinoscopy

In this technique, one of the methods described above is employed to induce accommodation (push-up or negative lenses) but the practitioner determines the end-point by observation of the retinoscopic refl ex. This technique can be used for patients with whom communication can be challenging (Woodhouse et al. 1993) or with patients who have a visual impairment (Leat and Mohr 2007). However, it requires skilled judgement by the practitioner (Leon et al. 2012; Roche et al. 2007; Wold 1967), which may explain why it is described less often than other methods. Only monocular measurement can be made, although measurement conditions can be monocular or binocular.

Table 1. **Types of error in clinical methods of measuring accommodative amplitude**

Source of error	**Method of measurement affected**					
	Push-up	Push-down	Push-down to recognition	Minus lens	Retinoscopy	Comments
Depth of focus	**	**	***	*	–	Major source of error
Reaction time	**	***	**	*	–	Major source of error
Reference point for measurements	**	**	**	–	**	Error can be eliminated
Instrumentation errors	***	***	***	–	**	Error can be eliminated
Practitioner bias	***	***	***	*	**	Error can be reduced
Errors specifi c to dynamic retinoscopy	–	–	–	–	**	Error can be reduced
Anomalous proximal cues	–	–	–	***	*	Error can be reduced

Sources of error

Seven types of error are discussed below and are linked to the methods described in Table 1. These are highlighted because they are relevant to the discussion below about improving accuracy, but it could be argued that sometimes these methods may be adequate. For example, in certain patients the need may be simply to demonstrate that AoA exceeds the patient's requirements. The sources of error are also likely to have influenced published normative values.

Depth of focus

In foveal viewing, the eye's depth of focus (DoF) is the range of an object's vergence at the eye without any blur being detected (Charman 2009). It is separate from accommodation. DoF arises partly because of inherent imprecision in optical focusing systems due to diffraction and aberration (Lipson et al. 2010) and partly because of limitations to the detection of blur. Detection of blur depends on acuity and on awareness of blur. This varies extensively, between patients, and with viewing conditions such as luminance.

DoF affects all of the methods of measuring AoA that require the patient to recognise blur. It was first assessed by comparing measurements of AoA using the push-up method to those by stigmatoscopy (Hamasaki et al. 1956), which uses the perceived sharpness of a spot of light to determine the refractive state of the eye, theoretically eliminating error caused by DoF (Lancaster 1934). Stigmatoscopy appears to lack validation and AoA research using this method has relied on older participants (Hamasaki et al. 1956) or small sample sizes (Sun et al. 1988).

The effect of DoF on the measurement of AoA with the push-up method has also been investigated by using targets of size that decreased as the target approached (Atchison et al. 1994). Results of AoA obtained using reduced-size test objects were around 75% of those obtained using test objects of constant size (N5). With real patients the end-point could be anywhere between the defocus that causes minimal blur and the greater defocus that blurs the test object just beyond recognition and this may result in a greater error than with trained research participants.

The DoF error may increase with accommodation owing to pupillary constriction and because the angular size of the target will increase with proximity (Jackson 1907; Rosenfield and Cohen 1995). There have been some attempts to control for this using a Badal optometer system (Ostrin and Glasser 2004; Somers and Ford 1983) such as the Lindsay accommodation measure (Figure 2), which was marketed in the 1950s.

The magnitude of error from DoF is infl uenced by target parameters (luminance, sharpness, contrast, shape and size: Kragha 1986; Tucker and Charman 1975), the observer's ability to perceive blur and pupil size. Pupil size changes with illumination, mental effort (Peavler 1974), age (Winn et al. 1994), accommodation itself (Charman and Radhakrishnan 2009) and many other diverse infl uences (Gilzenrat et al. 2012). Error due to DoF also varies with the method of measuring AoA.

Figure 2. Lindsay accommodation measure.

DoF is likely to be greater during near vision because of pupillary miosis and this may partly explain why the minus lens method gives lower results than the push-up method (Hokoda and Ciuffreda 1982, Ostrin and Glasser 2004; Rosenfield and Gilmartin 1990; Wold 1967), although DoF also slightly affects measurements with the minus lens technique (Momeni-Moghaddam et al. 2013). DoF may also explain why Ostrin and Glasser (2004) found much higher values of AoA with push-up than with four other methods.

As noted above, the error due to DoF may be limited clinically by reducing target size (Berens and Fonda 1950) and this idea was adopted in two investigations (Allen and O'Leary 2006; Atchison et al. 1994) but does not appear to have been otherwise taken up.

Reaction time

Reaction time is a source of error that influences all three of the methods that involve movement of the target. It is actually the sum of four reaction times that occur consecutively as the test object moves past the point where noticeable blur first occurs.

The four reaction times are the time it takes for the patient to register definite blur, to vocalise this, for the examiner to register that message and then for the examiner to stop the movement. The error can be limited by reducing target velocity, but slower rates of change may make the end-point harder to discern. Reaction time may influence push-up (detecting blur) differently to push-down (detecting clarity) and may also infl uence the minus lens method if the lenses are changed fast enough.

Benzoni and Rosenfield (2012) used reaction time to explain the common finding (eg Antona et al. 2009; Fitch 1971; Rosenfield and Cohen 1996) that results with the push-down method are lower than those with push-up. Woehrle et al. (1997) found that the push-up and push-down to recognition methods gave similar results. That could be because the error due to DoF in push-down to recognition was counterbalanced by reaction time error in push-up.

Reaction time error increases with target velocity when measuring accommodation on a distance (eg centimetre) scale. This effect is non-linear, as moving the test object a centimetre represents less than 0.1 D at a typical maximum accommodation level for a 40-year-old but about 0.5 D for a 10-year-old. It is therefore preferable to move the test object at a constant and slow rate of dioptres, rather than centimetres, per second. This is difficult to manage without automated equipment.

Some authors have described moving the target in step changes (Allen and O'Leary 2006; Atchison et al. 1994), which eliminates reaction time error but is tedious, and one group at a linear rate, 0.5D/s (Evans et al. 1994), which is difficult in practice. Others adopted quite varied non-linear rates, including 0.4 cm/s (Somers and Ford 1983), 1 cm/s (Adler et al. 2013) and 5 cm/s (Koslowe et al. 2010; Woehrle et al. 1997). At that speed, the effect of reaction time on the accuracy of their AoA measurements of around 20D would be quite large.

Reference point for measurements

This affects AoA test methods in which a distance is measured. It has been measured to: 14mm in front of the eye (Duane 1922); the spectacle plane (Turner 1958); the eye (Eames 1961; Kaufmann 1894; Moss et al. 1987); corneal plane (Anderson et al. 2008; Atchison et al. 1994); and 7mm behind the anterior corneal pole (Donders 1864). Some publications do not specify an end-point (Ayrshire Study Circle 1964; Rutstein et al. 1993). The use of different reference points produces greater error at higher levels of AoA. For example, if an eye had AoA of 3D measured to Donders' reference point, Duane would have recorded it as 3.2D; but 10D by Donders becomes 12.66D by Duane.

Instrumentation errors

Factors specific to the RAF Rule include ambiguity about the position of the slider's index on the scale, and uncertainty about the location of the scale's zero point (especially noting that different RAF rules appear to vary by at least a centimetre in the distance of any particular scale graduation from the cheek rest, as shown in Figure 3). There is further uncertainty concerning the relevance of the zero point, due to interindividual variations in facial anatomy.

Figure 3. Different RAF rule scales.

Furthermore, results with the RAF Rule are affected by how it is held, and there is conflicting advice about this (Keirl and Christie 2007; Rabbetts 2007). Typical variations in declination are shown by the patients in Figure 4. An equation can be found between the angles and distances involved. The equation shows that, with typical values of h = 4cm and k = 5cm and the accommodation levels and rule declinations measured, the subject tilting the rule down would appear to have just over 1 D more AoA, due to the tilt of the rule.

Figure 4. Variations in typical tilt of the RAF rule.

A small error may occur when comparing binocular with monocular conditions owing to monocular measurements lying on one eye's visual axis, whereas binocular measurements are taken on the midline. Measurements with the RAF rule are always on the midline. Turner (1958), Fitch (1971) and McBrien and Millodot (1986) corrected for this source of error.

Practitioner bias

This is a source of error in any measurement that is not fully automatic. The practitioner examining the patient will expect approximately where the measurement end-point should be. That expectation, and inevitable differences in technique between practitioners, may infl uence how the measurement is taken (eg target speed), which may in turn influence the result. It may affect naive patients more.

Research of accommodative response (Stark and Atchison 1994) and in fixation disparity (Karania and Evans 2006) has shown that the exact wording of instructions can influence the results of measurement. Adler et al. (2013) found a significant difference between five different examiners' results for push-up measurement of AoA and attributed this to examiners' measurement technique possibly differing slightly.

Errors specific to dynamic retinoscopy

Dynamic retinoscopy is typically conducted at a closer working distance (Jimenez et al. 2003; Leon et al. 2012; Roche et al. 2007; Rutstein et al. 1993) than static retinoscopy and this will reduce its precision (Atchison 2009) and increases the scaling error described above (1cm close to the eye represents a large dioptric change). This error would be reduced by adding negative lenses and this may be why this approach was adopted by Wold (1967), but this did not appear to improve measurement precision. Furthermore, the reliability of retinoscopy decreases when measuring away from the visual axis (Tay et al. 2011), which can occur in dynamic retinoscopy. Another issue with dynamic retinoscopy is glare and some authors have taken care to minimise this error (Roche et al. 2007; Wold 1967).

Anomalous proximal cues

Heath (1956) proposed that accommodative effort is driven by three signals: retinal, convergence and psychological. One psychological factor that influences accommodation is awareness of the test object's nearness (proximal accommodation), which has been found to be significant (Hung et al. 1996; Rosenfield and Gilmartin 1990). The minus lens method is an unnatural method of assessing accommodation, giving lower results because the proximal cue is avoided or reduced whilst accommodation is stimulated (Antona et al. 2009; Momeni-Moghaddam et al. 2013; Rosenfi eld and Cohen 1996).

Fitch (1971), with particularly careful methodology, found that accommodation measured with either the push-up or the push-down method is higher when the patient grasps and guides the target than when the examiner does. This could be due to various psychological factors, including increased awareness of proximity through proprioceptive feedback when the subject connects with the target and controls it.

Whatever method is used an adequate description of the test technique is required. This should include whether the measurement conditions are monocular or binocular, noting that binocular readings may be higher than monocular because of better binocular visual acuity (Pointer 2008), the effect of convergence directly (Morgan 1952) or via pupil size (Duane 1922) and more natural viewing conditions (Otake et al. 1993). Of course, in any measurement of AoA it is important to know the eye's refractive error and whether the accommodation is measured with the patient wearing spectacles or contact lenses.

Repeatability of methods

The following studies assessed the repeatability of routine clinical measurement of AoA in a similar young-adult age group. It should be noted that a method with good repeatability does not necessarily have good validity and may still be prone to the errors listed above.

Antona et al. (2009) measured the push-up, push-down and minus lens methods twice in 61 subjects using the same examiner throughout. They found that the 95% limits of agreement were best for the minus lens method (±2.52D) and worst for the push-up method (±4.76D).

The repeatability of the same methods was also assessed by Rosenfield and Cohen (1996) through measuring 13 subjects' AoA five times. They found that repeatability was similar for all three methods, and much better than Antona et al. found (95% confi dence limits circa ±1.42D) but still recommended that changes of less than 1.50D should be considered insignificant at this level of AoA (their participants were young adults).

Leon et al. (2012) assessed the minus lens method, a modified push-down method and dynamic retinoscopy. By measuring 76 subjects twice, they found that repeatability for the first two methods was similar to the findings of Antona et al. mentioned above. They also found that dynamic retinoscopy had much better repeatability than the other two methods that they reviewed.

Repeatability of the minus lens method was reviewed by Momeni-Moghaddam et al. (2013), who measured 43 young subjects twice and obtained good repeatability (95% confi dence limits circa ±0.83D).

Overall, the above reports suggested that the minus lens and retinoscopy methods were most repeatable. (However, these methods seem to be least commonly used in practice). Some of this effect can be explained as follows. If methods are of equal repeatability, those that give lower values for AoA (such as the minus lens method (Antona et al. 2009) and retinoscopy (Leon et al. 2012)) can be expected to give proportionately lower dioptric values for their 95% confi dence limits.

Other investigators have assessed repeatability of AoA measurement in different age groups. Chen and O'Leary (1998) measured, using push-down to recognition, twice in 18 subjects covering a wider age range. They found so little difference between the two occasions that it could be interpreted as negligible. Adler et al. (2013) measured 120 subjects aged 6–10 by push-up on three occasions, fi nding that 95% of subjects' measurements varied by up to about a quarter of the mean AoA measured.

Normative studies

Some of the key studies that provided normative values for AoA at different ages are summarised in Table 2. The most commonly cited reference values for the normal range of AoA are those of Duane (1922). Duane's results are the reference values printed on probably the most common UK instrument for measuring AoA, the RAF rule. 'Accommodation rule' is included in the list of 18 principal items of clinical equipment required for routine eye examinations in the UK (College of Optometrists 2012b). Duane's paper was the 59th most cited of all peer-reviewed clinical ophthalmic papers published globally before 1950 (Obha and Nakao 2010). Table 3 shows that, in optometry teaching, Donders and Duane are the most-quoted reference values for AoA. Duane's sample size was more than 30 times that of Donders (1864). A large sample size improves reliability and may give more information when analysed statistically. In the ground-breaking work by Donders, subjects covered the widest age range but were not otherwise described. Donders' results were presented unclearly (Fitch 1971; Hofstetter 1944), which may be why an appraisal of these results (Fitch 1971) found that values attributed to Donders often differed signifi cantly. This persists, as some textbooks of optometry (eg Elliott 2003; Rosenfield 2009) give substantially differing values for Donders' results, which appear best represented by Reading (1988).

Donders and other early investigators tended to use thin line test objects instead of an optotype, possibly as literacy was less common then. The relative merits of different test objects for measuring AoA are uncertain (Atchison et al. 1994).

Methodological limitations are often apparent in older work and this may explain the common reporting of a curiously stable and clinically substantial residue of accommodation never lost to age. Methodology developed and it is now generally accepted that most people have completely lost the ability to accommodate just after age 50 (Charman 1989).

Table 2. Key studies that included population data on amplitude of accommodation

Author	**Year published**	**Method**	**Number of eyes or subjects**	**Subjects' age (years)**	**Main factors that may infl uence reliability**
Donders	1864	Push-up	130 subjects	10–80	No assessment of refractive error
Kaufmann	1894	Push-up	400 eyes of all subjects	5–74	No assessment of refractive error
Jackson	1907	Push-up	Most eyes of 3346 subjects	5–70	Retrospective, some refractive error assessment
Sheard	1920	Minus lens	Several hundred eyes	15–40	Object at 33cm
Duane	1922	Push-up	Most eyes of about 4000 subjects	8–72	
Jackson	1922	Minus lens	Unknown	10–65	Binocular
Clarke	1924	Push-up	Most eyes of over 5000 subjects	10–65	Retrospective, used Duane's method
Coates	1955	Push-up	3171 eyes of about 1700 subjects	10–80	Retrospective, no assessment of refractive error
Turner	1958	Push-down	About 1000 eyes of about 500 subjects	10–75	Retrospective
Ayrshire Study Circle	1964	Push-up	1307 subjects	30–75	Limited details of methodology
Fitch	1971	Push-up and push-down	110 subjects	13–67	
Anderson et al.	2008	Open-fi eld autorefractor and minus lens	140 eyes	3–40	

Table 3. Methods that textbooks give for measuring amplitude of accommodation

Author	Year published	Main method recommended	Other methods given	Push-up/down object size if recommended	Parameter standardisation suggested	Norms given
Abrams	1993	Push-up	None		None	None
Barratt	2013	Push-down to recognition	Minus lens, push-up		None	None
Grosvenor	2007	Push-up	Minus lens	N4 approx.	None	Donders
Keirl and Christie	2007	Push-up	Push-down, mean of push-up: push-down to recognition, retinoscopy	N6 approx.	None	Unattributed
Rabbetts	2007	Push-up	Badal optometer, minus lens, push-down, retinoscopy		None	Duane
Reading	1988	Push-up	Minus lens, retinoscopy		None	Donders, Duane, Other
Rosenfi eld	2009	Push-up	Badal optometer, minus lens, push-down, retinoscopy, mean of push-up :push-down		None	Donders, Duane, Other

The survey by Turner (1958) was the first to standardise the target's luminance contrast (although the target detail was large) and to use the push-down method. Turner measured each eye of 500 subjects: such pooling of both eyes' data in statistical analysis has been criticised (Ederer 1973). Three studies (Clarke 1924; Duane 1922; Turner 1958) used cycloplegic refraction in some subjects, although the selection criteria for this were not clear.

The Ayrshire Study Circle (1964) investigation included a large sample size but lacked methodological details and statistical analysis. It was alone in finding that AoA showed gender differences: meta-analysis (Hickenbotham et al. 2012) found no evidence for gender influencing the onset of presbyopia through AoA.

Some of the studies shown in Table 2 described subjects' race and, more often, gender, but these characteristics were not described in other studies (eg Duane 1922). This makes it diffi cult to aggregate studies (Allen and O'Leary 2006). Variations in study characteristics and the factors in Table 1 may explain why the results of these normative studies differ substantially at any subject age. For example, the results of Donders, as reported by Reading (1988), are about half as large again as those of Turner (1958) at almost any subject age. Anderson et al. (2008) obtained results still lower than Turner's.

Hofstetter (1944) made a thorough comparison of three of the studies shown in Table 2 (Donders 1864; Duane 1922; Kaufmann 1894) in an attempt to provide defi nitive normative data. The three studies used push-up line test objects but there were some methodological differences between them. However, even taking those differences into account, Hofstetter could not reconcile the Duane and Donders results (but noted that Kaufmann may have replicated Donders quite closely). There would appear to be a need for more research on normative values using standardised methods, as discussed below.

Can current test methods be standardised?

Setting normative values for a clinical measurement requires research that measures it in sufficient numbers of well-specifi ed subjects using standardised procedures. Typically, the normative range is defined as that which encompasses 95% of values (Gardner and Altman 1989). However, as shown above, there is marked variation in published norms of AoA and therefore abnormal values cannot be identified with certainty.

Ideally, a standardised measurement method should be used in normative studies and the same standardised method should then be employed by clinicians so that their results can be directly related to the published norms. An inspection of contemporary clinical textbooks (Table 3) reveals that most, but not all, recommend variations on the push-up method. However, Table 3 also reveals that there are very few attempts to standardise test conditions that may limit the errors cited in Table 1. In the long term, it would be useful to develop improved instrumentation to measure AoA. In the interim, it would seem sensible to attempt the following standardisation to the push-up method:

- Limit the effect of DoF by using typical lighting for work requiring perception of fine detail, 500 Lux (HSE 1997), and small targets (eg N3).
- Minimise reaction time errors by standardising speed linearly or by making step changes.
- Standardise the reference point for measurement (eg to the corneal apical plane).

● **Summary**

Community optometrists measure the AoA, typically comparing their results with normal values derived from population surveys. The AoA is commonly tested in children and the need for such testing in older patients will increase, for example, to assess the performance of various methods of reinstating accommodation, such as 'pseudo-accommodative' IOLs. Several methods are available to measure the AoA and the strengths and weaknesses of each approach have been discussed, with comments on the intertest and intratest reliability. Suggestions have been made for improving and standardising the clinical assessment of the AoA.

Conclusion

AoA is a fundamental optometric measurement but the literature shows methodological sources of substantial error in its routine clinical measurement. These errors also call into question the values given in the literature for amplitude age norms, which vary considerably. Some suggestions have been made for standardising and improving current clinical methods of measuring AoA. Updated normative values using improved measurement methods would also be valuable.

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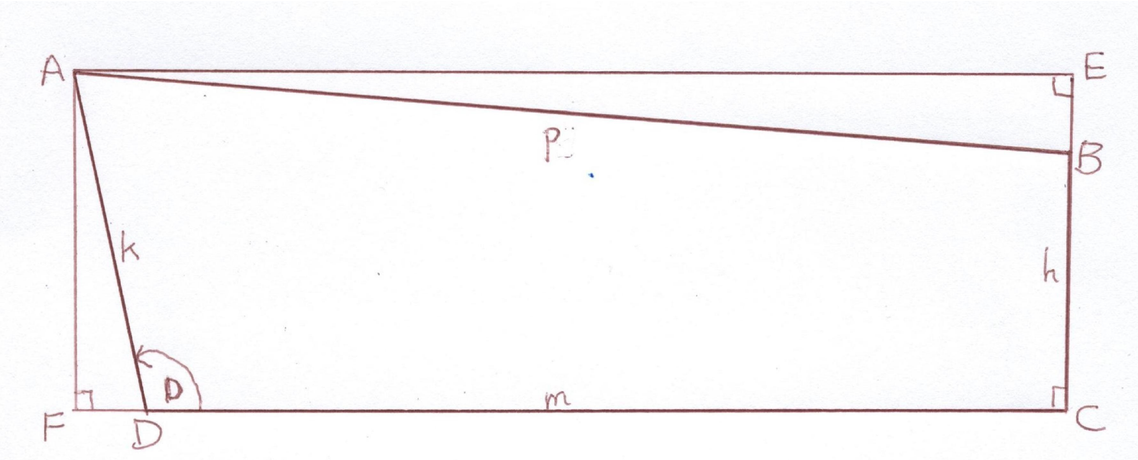
Appendix 2 The effect, on its measurements, of tilting the RAF Rule



A is corneal vertex

B is visual object, of RAF Rule, on which

C is nearest point to B on rule's rail

D is midpoint between cheekrests

p mm, = AB, inversely related to the vergence measured = 1000/p D

<u>To find the difference between 1000/p when RAF Rule tilted up to when it is tilted down:</u>

taking typical values:

m, from midpoint between cheekrests to point on rail nearest to B = DC = 150 mm

k, from corneal vertex to midpoint between cheekrests, = AD = 50 mm

h, from visual object to rail = BC = 40 mm

angle ADC is declination of Rule; in Figure 2.3, 115° (upper photo, and diagram above) and 80° lower photo

Rectangle AECF is constructed by producing BC and BD.

p = AB = $\sqrt{}(AE^2 + EB^2)$ so, to find AE and EB (NB: FD is –ve if ADC > 90°)

AE = DC + FD = 150 - AD.cosADC = 150 – 50cosADC

EB = AF – BC = AF - 40 = $\sqrt{}(AD^2 - FD^2)$ – 40 = $\sqrt{}(625 – 625\cos^2 ADC)$ - 40

Hence p = $\sqrt{}((150 - 50\cos ADC)^2 + (\sqrt{}(625 – 625\cos^2 ADC) - 40)^2)$

Substituting the values for angle ADC above

Rule tilted up: 1000/p = 7.034 D, and Rule tilted down: 1000/p = 5.814 D

Therefore, the difference due to tilt, taking these typical values, = <u>1.22 D</u>.

Appendix 3 Approvals obtained for the research

LSBU:

London South Bank
University

Direct line: 020-7815 6025
E-mail: mitchen5@lsbu.ac.uk
Ref: UREC 1318

David Burns
11 Britannia Road
London N12 9RU

Dear David,

Re: Investigation of a new clinical method of measuring amplitude of accommodation

Thank you for submitting this proposal and for your response to the reviewers' comments.

I am pleased to inform you that Full Chair's Approval has been given by Chair on behalf of the University Research Ethics Committee.

I wish you every success with your research.

Yours sincerely,

N Mitchell

Nicola Mitchell

Secretary, LSBU Research Ethics Committee

cc:

Prof Shushma Patel, Chair, LSBU Research Ethics Committee

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Institute of Optometry:

Ronald Rabbetts, MSc, FCOptom, SMSA, DCLP
31 Warblington Street
PORTSMOUTH, PO1 2ET

Phone: 023 92816571
Email: ronald.rabbetts@virgin.net

02 May 2013

Reference:

Application from Mr David Burns for research for his Doctorate of Optometry:

Investigation of a new clinical method of measuring amplitude of accommodation

To: The Chair of the LSBU Research and Ethical Committee

My colleagues and I on the Institute of Optometry's Research and Ethical Committee have read David Burn's LSBU Research application. Several suggestions were made from an optometric point of view. Mr Burns has either dealt with these in the revised application documents or replied to our concerns in his reply document.

On behalf of the Institute of Optometry Research and Ethical Committee, I am happy to confirm our agreement on the revised documents, and trust that you will approve the application so that the research project can go forward.

Yours sincerely

Ronald Rabbetts

Ronald Rabbetts,
Chairman, Institute of Optometry's Research and Ethical Committee

IRAS:

North Middlesex University Hospital NHS

NHS Trust
Research & Development Office
Sterling Way
London N18 1QX
Direct Line: 020 8887 2307
E-mail: Hannah.olugemi@nhs.net
Date: 22.10.15

NHS PERMISSION FOR RESEARCH (R&D Approval)

Dear Colleague/s

IRAS ID: 186959
REC Ref: UREC 1318
NMH RAP: ~~687~~ 700

Study Title: Comparison of clinical measurement methods of accomodative amplitude

NHS permission for the above research has been granted for the following NHS Trusts and/or Independent Contractors:

Trust/Independent Contractor	Name of PI / LC	Date of Permission
North Middlesex University Hospital NHS Trust	Dr David Burns	08 October 2015

Permission is based on the REC favourable opinion.

Permission is granted on the understanding that the study is conducted in accordance with the Research Governance Framework, ICH GCP, and the policies and procedures of the Trust/s [http://www.crn.nihr.ac.uk/resources/trusts-covered-by-crn-north-thames/?h=42].

Permission is only granted for the activities for which a favourable opinion has been given by the REC [and which have been authorised by the MHRA].

Specific Conditions of Permissions (if applicable)
Debbie Levene would require a Letter of Access before she can commence research at North Middlesex University Hospital NHS Trust

Yours Sincerely,

Jonathan Ainsworth
Director of Research & Development
Cc: Chief investigator, Sponsor Contact, Research Site R&D Office/s

Putting people first

Chair: John Carrier   Chief Executive: Julie Lowe

`

Appendix 4 Recruitment flier

Appendix 5 Recruitment letter to principal investigator's patients

David Hillel
Optometrists Contact Lens Practitioners

119 High Road
East Finchley
London N2 8AG

Tel: 020 8444 2233
Freephone: 0800 432 0204

www.davidhillel.co.uk
info@davidhillel.co.uk

Dear

This letter has been sent to you because I am seeking to recruit people to help with my university research project and I hope that you might be interested. It is not about your personal eyecare.

The attached flier introduces the project. If you might be interested in volunteering for the research, the next stage will be for me to send you the detailed information sheet. Whether you decide to take part in this project, or not, your normal attention here for the eyes and sight will definitely not be affected as it is separate from that.

I am also recruiting people to take part in the research from individuals who have not been patients of this practice. So, if you know of anyone from 18 to 43 years of age who may be interested in participating then please do let them know about this. All participants can enter the free Prize Draw.

Please contact me for the information sheet if you might like to consider taking part. The information sheet is also at www.davidhillel.co.uk/research .

Yours sincerely

David Hillel Burns Optometrist
BSc(hons) MSc MPhil FCOptom DCLP

Appendix 6 Participant information

London South Bank

University

Research Project:

<u>Investigation of a New Clinical Method of Measuring Amplitude of Accommodation</u>

Please help in this vision research project.

I am an optometrist, studying eyesight in a scientific research project at London South Bank University and the Institute of Optometry, and I am looking for people to volunteer for the project. Thank you for expressing interest.

You are invited to take part in this research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask me if there is anything in it that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

What is the purpose of the study?

It is to study the extent of accommodation, which is how the eye automatically focuses at different distances. This project is to compare different ways of measuring accommodation, to find out which is the best way. I hope that this will help people to see more clearly. The research has begun and is expected to run until early in 2015.

Who can take part?

People who are between 18 and 43 years of age and can see quite well with or without spectacles or contact lenses.

Does anyone have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form before you start. You will be given a signed copy of the consent form and you will remain free to withdraw at any time and without giving a reason. A decision to withdraw at any time, or a decision not to take part, will not affect the standard of care given by your optometrist or optician.

What will taking part be like?

- It will be for two separate sessions each of less than an hour, at times to suit you within the advertised opening hours of the practice.
- The research will be in the optician - optometrist practice David Hillel, 119 High Road, London N2 8AG
- It will be comfortable, not strenuous at all, with no side-effects. You will not be asked to use any drugs or eyedrops.
- It will be unpaid but refreshments and agreed expenses such as for public transport within five miles will be available.

If you wear spectacles or contact lenses it is best, though not essential, to bring them. You are welcome to bring a companion.

You will be asked your date of birth and brief contact details, and to sign the University's consent form which is the same form as the one included with this information. Then I will look at one eye from arm's length with an optician's measuring torch shining a small light for a few seconds. After that, I will ask you to read a few letters with the other eye covered, to check how each eye focuses. (If this shows anything unusual, which is very unlikely, I will advise you to see an appropriate eyecare practitioner about it and you may still continue to take part if you wish).

This will be followed by your wearing spectacles with removable lenses, like the ones often used by optometrists in their normal work, reading letters a few times on a small, simple, hand-held chart or on a simple holder rested lightly on the cheeks.

The second session will be more than a week after the first session. It will involve repeating the letter-reading measurements from the first session (except the lens-assisted measurements) and some of those will be with a different optometrist. There will also be some readings using a tabletop instrument that measures the eye’s focussing by the participant simply looking through a window in it. Everyone who completes the research will be entered for the free prize draw for a new iPad Mini with two runner-up prizes of a pair of classic RayBan sunspecs. Winners will be notified after the experimental work finishes. It is hoped that the draw will take place at the East Finchley Christmas Festival in 2015.

What are the possible disadvantages and risks of taking part?

This has been given careful consideration and no disadvantages or risks have been identified, though it is appreciated that participants will be giving up their time.

What are the possible benefits of taking part?

You would contribute to improvement in the care of eyesight, and you may win a prize.

What if something goes wrong?

If you have a complaint or confidential problem related to this research please contact either my supervisor, Professor Bruce Evans, Institute of Optometry, 56-62 Newington Causeway, London. SE1 6DS, bjwe@bruce-evans.co.uk; or University Research Ethics Committee Chair, London South Bank University, 103 Borough Road, London SE1 0AA, ethics@lsbu.ac.uk.

Will my taking part in this study be kept confidential?

Yes. All of the information collected by this research will be kept strictly confidential. All data shared with any other person or organisation will have name and address removed, so that you cannot be recognised from it, and all records will be erased on Jan 1 2020.

What will happen to the results?

I hope that the overall results will be published in academic journals for eye-care professionals.

Who has reviewed the project?

Two Research Ethics Committees: that of London South Bank University, and that of the Institute of Optometry

Contact for further information

If you would like to take part or if you would like more specific information, please contact me. I am in the optician's by the zebra crossing, at 119 High Road, East Finchley, London N2 8AG, tel 0208 444 2233 or email office@davidhillel.co.uk .

Once more, thank you for reading this. I hope you will consider it at leisure, discuss all this with others if you wish, and then decide if you would like to book a research appointment. If you have left your contact details and I have not heard from you after a week, I may contact you once more to ask if you are interested in participating. If you say no, or don't reply to my message, I promise not to bother you again!

Yours sincerely

David Hillel Burns BSc(hons) MSc DCLP MPhil FCOptom

Optometrist, registered with the General Optical Council since 1974, and LSBU professional doctorate student

Appendix 7 Participant Consent Form

London South Bank

University

CONSENT FORM FOR PARTICIPATION IN RESEARCH STUDY: "Investigation of a new clinical method of measuring amplitude of accommodation"

Researcher: David Hillel Burns, LSBU student

I have read the attached information sheet on the research in which I have been invited to participate and have been given a copy to keep. I have had the opportunity to discuss the details and ask questions about this information.

The Investigator has explained the nature and purpose of the research and I believe that I understand what is being proposed. I understand that my personal involvement and my particular data from this study will remain strictly confidential, and that I am free to withdraw from the study at any time without giving a reason for withdrawing. I have been informed about what the data collected in this investigation will be used for, to whom it may be disclosed, and how long it will be retained. I understand that, if I am a patient of David Burns, my participation in, or subsequent withdrawal from, the research, will not influence the care I receive at Mr Burns' practice.

I hereby fully and freely consent to commence participation in the study.

Participant's name in block capitals:..

Participant's age ....

Participant's preferred contact details – only for non-marketing use eg reminding of the repeat visit where applicable:

....

....

Participant's Signature: ....

Date:...

As the researcher responsible for this study I confirm that I have explained to the participant named above the nature and purpose of the research to be undertaken.

Principal Investigator's Name: David Hillel Burns

Principal Investigator's Signature:..

Date: ....

Participant's confidential identification number for this study only: ………………………………………...

Appendix 8 Results with masked rules

Ruler	*1*	*2*	*3*	*4*	*5*	*repeat*	*repeated*
Participant							
1	NS7	LT2	YF5	DW6	QA8	DW6	4
2	FL7	VG0	HA8	BS8	LP8	LP8	5
3	YD4	RV3	EV3	AR6	WB7	LZ3	1
4	FL4	WM7	MR5	KN2	BF1	FL9	1
5	UV6	CP8	TH5	EQ5	JC8	YD8	1
6	UV6	CP3	TH5	VL7	JC8	UV8	1
7	AR5	QB5	SL6	AF4	HV0	HQ3	1
		Coded readings (magnified mm):					
1	217	182	205	226	198	226	
2	247	220	238	258	228	228	
3	274	243	263	296	257	283	
4	244	217	245	262	231	249	
5	266	238	255	285	248	278	
6	266	233	255	277	248	268	
7	195	175	186	204	180	203	
ruler grads	30	27	29	32	28		
ruler cm	27.65	27.9	27.68	28.32	27.87		
hence ruler magnification	0.9217	1.0333	0.9545	0.8850	0.9954		
		hence real distances (mm):					
1	200	188	196	200	197	200	
2	228	227	227	228	227	227	
3	253	251	251	262	256	261	
4	225	224	234	232	230	229	
5	245	246	243	252	247	256	
6	245	241	243	245	247	247	
7	180	181	178	181	179	187	
		converted to dioptres:		mean of	all =	4.4871	
1	5.0000	5.3173	5.1107	4.9998	5.0741	4.9998	
2	4.3927	4.3988	4.4020	4.3796	4.4064	4.4064	
3	3.9598	3.9825	3.9836	3.8174	3.9092	3.8339	
4	4.4467	4.4596	4.2763	4.3128	4.3492	4.3574	
5	4.0789	4.0661	4.1086	3.9647	4.0511	3.9028	
6	4.0789	4.1534	4.1086	4.0792	4.0511	4.0485	
7	5.5641	5.5300	5.6327	5.5389	5.5815	5.3448	

This gives 95% LOA of ± 3.17%.

Appendix 9 Validation of the Grand Seiko WAM-5500 for measuring the refraction of the accommodated eye

This reports very small-scale ancillary work by the author of this study to validate the autorefractor at the levels of accommodation measured in this study. This work compared the instrument's measurements of accommodative response with preset proximal stimuli. It also compared the instrument's measurements to lens power added when accommodation was inactive. The following methods were used: resolving the finest detail possible at a series of distances, locking accommodation by the fellow eye fixating a fine distant target and adding contact lenses, cycloplegia adding trial lenses, presbyopia adding trial lenses, and presbyopia, adding contact lenses. The first four methods all gave an accommodative response of about 80% at maximal and other levels of accommodation, and the fifth about 92%.

The five experiments are summarised here. Their outcome data were right eye refraction readings made with the autorefractor. Participants' visual acuities exceeded 6/6, their refractive errors were corrected and their amplitudes of accommodation measured with the TRU exceeded the accommodative stimulus levels except as specified below.

In experiment (1) five participants resolved the smallest detail possible at distances giving vergences of 2.44D, 4.12D and 6.25D, viewing binocularly. Their mean of about sixteen responses each to these three accommodative demands averaged 83.0%, 84.1% and 80.6% respectively. The range for participants' means was 68% to 96% and did not correlate with participants' AoA.

In experiment (2) the two fully-presbyopic participants wore soft contact lenses from -2D to +8D in 1D steps on the eye being measured. Each participant gave about sixteen measurements with each contact lens and with no lens. The mean results averaged 93.0% of the expected reading. This response was similar for both participants and approximately linear.

In experiment (3) a presbyope wore spectacle trial lenses from 0 to +8D in 1D steps, corrected for their distance from the eye, and nine readings were made for each. Readings, quite constant for each lens, were 75% to 91% of the added power (average 80.9%, added powers above 2D all giving lower readings).

In experiment (4) a non-presbyope wore soft contact lenses (thirteen added contact lens powers from zero to +8D) on the measured eye which viewed a frosted glass just beyond the autorefractor mirror. Meanwhile, accommodation lock was attempted by the participant concentrating with the other eye on far distant detail just above her acuity threshold. Measurements averaged 87.4% of the expected reading, and varied moderately as if the accommodation lock was not fully effective.

In experiment (5) two non-presbyopes under cycloplegia wore spectacle trial lenses while ten readings were made for each added lens from 0 to +8D in 1D steps. These were corrected for their distance from the eye. The mean response was 85.5% of the demand, tending to be more in higher added powers, with only weak agreement between the two participants.

The WAM-5500 thus appeared to give substantially low measurement of accommodation (though not quite as low as published research mentioned in Section 6.6.7) and almost as low when power was instead added with spectacle or contact lenses.

Appendix 10 Written TRU instructions for the secondary investigator

How to do the RAF Rule

Seat the person comfortably wearing the left-frosted spectacle and hand them the RAF Rule, showing how to hold it. Move the slide to the far end and show the word "custom" checking for correct lighting on it. Comment that the word is sharp and clear, obtaining agreement.

Say you will bring it nearer and to tell you as soon as it gets the slightest blur although concentrating to keep it just as clear. Then bring the slide nearer, at about a dioptre every four seconds.

When the first blur is reported, stop and ask if with concentration it regains its sharpness. If yes, resume as the last paragraph, once.

Stop at the initial slight but definite blur and record the slide's reading, in mm.

How to do the TRU

You will need a TRU, the list of TRU letters, and a rule.

Seat the person comfortably wearing the left-frosted spectacle. Switch the TRU on and hand it to the person saying "Holding this as close to the eyes as you like, please read as many of the tiny letters as you can down the far right-hand column".

Sometimes you might get the feeling that maybe, and for whatever reason, they aren't trying very hard. If no letters are read in the end column, start off with the next column and, if that all gets read OK, encourage reading of the end column. If you suspect shyness to hold it closer, say "try holding it a little nearer or a little further away" so they try that and then you say "OK, put it where it's best to read the tiniest letters".

When the smallest letters are being read, say "Hold it exactly there please" and measure the distance from the corneal apex to the letters. Record that distance.

Abbreviations in this thesis

A	Autorefractor measurement
ANOVA	Analysis of Variance
AoA	Amplitude of Accommodation
BMPV(95%)	Biometric Mean Pair Variation for 95% confidence limits
cm	Centimetre(s)
.csv	Comma separated variable
CV	Coefficient of Variation
D	Dioptre(s)
DoF	Depth of Focus
DS	Dioptres of spherical power
H	TRU letter height
IRAS	Integrated Research Application System
ISN	Individual Sequential Number
LOA	Limits of Agreement
mm	millimetre(s)
MPV	Mean Pair Variation
nm	Nanometre(s)
P	Position in TRU letter sequence
p	Probability of null hypothesis
R	RAF Rule measurement of AoA
RAF	Royal Air Force
SD	Standard Deviation
SE	Standard Error
sec	Second(s)
T	TRU measurement
TRU	Threshold Resolution Unit
VA	Visual Acuity
VN	Visual Acuity at the near point