Reading Without Central Vision:

Effects of Text Spacing on Reading in Patients with Macular Disease

Sally Blackmore-Wright BSc (hons) MC Optom

Doctorate in Optometry

School of Life and Health Sciences

Aston University

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Abstract: Loss of central vision caused by age-related macular degeneration (AMD) is a problem affecting increasingly large numbers of people within the ageing population. AMD is the leading cause of blindness in the developed world, with estimates of over 600,000 people affected in the UK.

Central vision loss can be devastating for the sufferer, with vision loss impacting on the ability to carry out daily activities. In particular, inability to read is linked to higher rates of depression in AMD sufferers compared to age-matched controls. Methods to improve reading ability in the presence of central vision loss will help maintain independence and quality of life for those affected.

Various attempts to improve reading with central vision loss have been made. Most textual manipulations, including font size, have led to only modest gains in reading speed. Previous experimental work and theoretical arguments on spatial integrative properties of the peripheral retina suggest that 'visual crowding' may be a major factor contributing to inefficient reading. Crowding refers to the phenomena in which juxtaposed targets viewed eccentrically may be difficult to identify. Manipulating text spacing of reading material may be a simple method that reduces crowding and benefits reading ability in macular disease patients.

In this thesis the effect of textual manipulation on reading speed was investigated, firstly for normally sighted observers using eccentric viewing, and secondly for observers with central vision loss. Test stimuli mimicked normal reading conditions by using whole sentences that required normal saccadic eye movements and observer comprehension. Preliminary measures on normally-sighted observers (n = 2) used forced-choice procedures in conjunction with the method of constant stimuli. Psychometric functions relating the proportion of correct responses to exposure time were determined for text size, font type (Lucida Sans and Times New Roman) and text spacing, with threshold exposure time (75% correct responses) used as a measure of reading performance. The results of these initial measures were used to derive an appropriate search space, in terms of text spacing, for assessing reading performance in AMD patients.

The main clinical measures were completed on a group of macular disease sufferers (n=24). Firstly, high and low contrast reading acuity and critical print size were measured using modified MNREAD test charts, and secondly, the effect of word and line spacing was investigated using a new test, designed specifically for this study, called the Equal Readability Passages (ERP) test.

The results from normally-sighted observers were in close agreement with those from the group of macular disease sufferers. Results show that: (i) optimum reading performance was achieved when using both double line and double word spacing; (ii) the effect of line spacing was greater than the effect of word spacing (iii) a text size of approximately 0.85^{o} is sufficiently large for reading at 5^{o} eccentricity. In conclusion, the results suggest that crowding is detrimental to reading with peripheral vision, and its effects can be minimized with a modest increase in text spacing.

Key Words: Crowding; Reading Speed; Word Spacing; Line Spacing; Macular Disease.

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The software used to collect the preliminary measures (Section 2.0) was written by Professor S.J. Anderson. Implementation of published routines for fitting psychometric functions (Section 2.0) was completed using software written by Professor M.A. Georgeson.

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List of Contents

List of Figures

List of Tables

List of Appendices

Reading Without Central Vision: Effects of Text Spacing on Reading in Patients with Macular Disease

1.0 Introduction

Loss of central vision, principally through age-related macular degeneration (AMD), can have a devastating effect on daily life. Various attempts have been made to improve reading in patients with a central scotoma, with magnification of text being the usual method. Hand held optical magnifiers and electronic magnification devices are a popular source of magnification.

The effect of crowding may be a significant factor when reading with eccentric vision. Crowding is the deleterious effect of nearby contours on target recognition. The potency of crowding increases with eccentricity from the fovea. Modifying the spacing between text characters may reduce the effects of crowding and improve readability for AMD patients.

This thesis will investigate the effect of text spacing on reading speed for (i) normally sighted observers (n=2) and (ii) a group of AMD patients (n=24). The text spacing that provides optimal reading conditions for the study participants will provide guidelines for optimal text spacing to use for readers with central vision loss.

1.1 Overview of Age Related Macular Disease

AMD is a chronic and progressive disorder of the retina. It is the leading cause of sight impairment in the western world, with estimates of 608,000 people currently affected by AMD in the United Kingdom. These numbers are expected to rise by 25% by the year 2020 (Minassian et al., 2011, Mitchell and Bradley 2006, Owen et al., 2003). The condition can occur in adults of all ages, but is most common in people over 40 years old. Of those registered severely sight impaired in the United Kingdom, 42% of those aged between 65-74 years of age have sight loss caused by age-related AMD, rising to 66% in the 75-84 years age group and 74% in those aged over 85 years (Bunce and Wormald, 2008). Prevalence is ten times higher in Caucasians compared with Afro-caribbean's (Friedman et al., 1999), and the prevalence in Asians is thought to be similar to that of Caucasians (Laude et al., 2010).

Risk factors for age related AMD include age (Gehrs et al., 2006, Freidman et al., 2004, Smith et al., 2001), obesity (Peeters et al., 2008, Seddon et al., 2003), cigarette smoke (Chakravarthy et al., 2010, Thornton et al., 2005, Seddon et al., 1996), low intake of zinc (Erie et al., 2009), low dietary intake of lutein (Izumi-Nagai et al., 2007) and omega 3 fatty acids (Pilkington et al., 2011, Seddon et al., 2006 and Chong et at., 2008), hypermetropia (Lavanya et al., 2010, Sanberg et al.,1993) and genetic markers (Ngai et al., 2011, Hageman et al., 2011, Edwards et al., 2005). There is evidence to suggest that the intake of dietary supplements, including macular carotenoids, lutein and zeaxanthin, may slow the progression of the disease (Eye Disease Case-control Study Group, 1993, Snellen at el., 2002, Lim et al., 2012 and Chew et al., 2013). Such supplements are widely available from health care retailers and are commonly self-prescribed by the general public in an attempt to protect themselves from the effects of AMD.

AMD progressively affects central vision, with early changes to monocular central vision often being asymptomatic. As the condition progresses vision becomes increasingly affected, with visual symptoms including distortion of straight edges and central grey smudges or haze. AMD is usually bilateral, with one eye affected sooner than the fellow eye. As the disease progresses central vision continues to worsen, until eventually it is lost altogether, leaving a central scotoma.

1.1.1 Dry Macular Degeneration

The first clinical signs of age-related AMD are drusen deposits beneath the retinal pigment epithelium (RPE), at the level of Bruch's membrane (see Figure 1). Drusen consists of accumulated extracellular material that appears on biomicroscopy as yellow white spots, often within the macular area. The mechanism of its deposition remains unclear, with theories implicating the activation of the immune system in drusen formation, and also the reduced ability of the choriocappilaris to remove extracellular debris from the highly metabolically active RPE with advancing age. Drusen gives overlying RPE a mottled appearance and this is a pathological landmark of both dry and wet AMD (Doyle et al., 2012).

Drusen can be described as being either hard or soft. Hard drusen is usually asymptomatic and forms small discrete yellow spots on the retina which will have localised overlying RPE dysfunction. Soft drusen can cover much larger areas than hard dusen, with irregular contours and the ability to coalesce. Both types of drusen cause elevation and mechanical stress to the overlying RPE, which causes depigmentation and atrophy to the RPE cells. The loss of RPE cells and a reduced ability for oxygen and nutrients to reach the retina from the choriocapillaris causes vision loss.

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Figure 1: Dry macular degeneration. *Biomicroscopy shows retinal drusen at the macular. These extra-cellular deposits are a landmark of dry macular degeneration (*Image taken from *Simple Anatomy of the Retina, http://webvision.umh.es, 2012).*

As dry macular degeneration progresses, the retina, RPE and choriocappilaris become disrupted and damaged to such an extent that the tissue becomes atrophic. Atrophy is seen clinically as sharply demarcated areas of hypopigmentation, often termed geographic atrophy (see Figure 2). Areas of geographic atrophy have no ability to detect light and therefore cause total scotomata within the visual field. Research into possible treatment of dry macular degeneration is currently underway. However, at the current time there are no FDA approved treatments for dry macular degeneration. The reduction in visual acuity and enlargement in central distortion progresses at a slower rate in dry AMD than wet AMD. In the UK, 40,0000 people per year convert from dry age-related AMD to wet (Owen et al 2012).

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Figure 2: Subretinal fibrosis. *Subretinal fibrosis (disciform scar) appears on biomicroscopy as areas of hypopigmentation which correspond to absolute scotomas in the visual field* (Image taken from *North Suburban Vision Consultants, http://www.nsvc.com ,2013).*

1.1.2 Wet Macular Degeneration

Wet macular degeneration can reduce central vision suddenly and severely. In wet macular degeneration, choroidal neovascular tissue breaks through Bruch's membrane into the neural retina. The weak fragile vessels of the choroidal neovascular membrane leak fluid, lipid and blood into the delicate layers of the retina which quickly leads to a reduction of vision (see Figure 3). Patients present with symptoms of sudden onset metamorphopsia, photopsia and central scotoma. The fluid may eventually be reabsorbed by surrounding tissue, however fibrous tissue and scarring of the retina will cause permanent and potentially substantial vision loss.

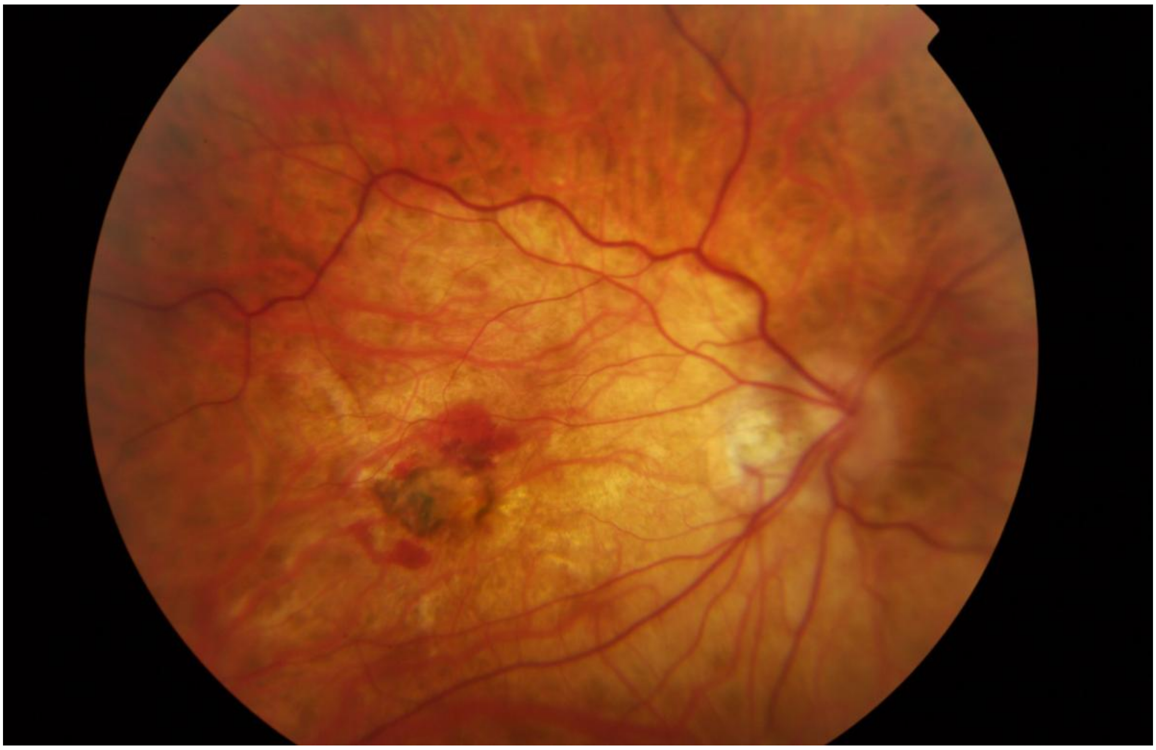

Figure 3: Wet macular degeneration associated with atrophic changes in the RPE. *Leaking neovascular membranes cause accumulation of retinal fluid and haemorrhage (image from authors own collection).*

In contrast to dry AMD, treatments for wet AMD have been offered for several years in UK eye departments. Intravitreal triamciniolone injections, photodynamic therapy and argon laser photoablation have all served to destroy choroidal neovascular membranes. The current method of treatment for wet AMD in the UK is usually monthly intravitreal injections of ranimizumb or bevacizumab. Both of these drugs are vascular endothelial growth factor (VEGF) antagonists. The growth hormone VEGF regulates angiogenesis and is critically involved in the formation of choroidal neovascular membranes. The intravitreal injections of VEGF antagonists aim to occlude the new fragile vessels of the choroidal neovascular membrane and inhibit VEGF, therefore preventing further membrane growth.

Ranibizumab (Lucentis, Genentach/Novartis) is an antibody fragment whereas bevacizumab (Avastin, Genentech) is a full length antibody that binds to all isoforms of VEGF. The difference between Avastin and Lucentis from a commercial view point is that the former can be supplied at a fraction of the cost of the latter.

Treatment duration can range from 3 months to several years depending on the response of the choroidal neovascular membrane to treatment. VEGF antagonist intravitreal injections can sometimes be combined with photodynamic therapy to enhance results.

Injecting VEGF inhibitors directly into the vitreous acts to reduce the risk of acuity loss (Rosenfeld et al., 2006). In 2010, the NHS spent £129 million funding Lucentis injection to treat patients with wet macular degeneration in the UK (RNIB, 2012). Since the introduction of VEGF antagonists, data suggests there has been a reduction in blindness attributable to AMD by approximately 50% (Bloch et al, 2012). Therefore usable central vision is maintained for longer in the AMD population. People who otherwise would have end stage AMD with the associated severe sight loss, instead are living with more modest visual impairments.

1.2 Effect of Visual Impairment

Central vision loss can cause difficulties with daily tasks and induce emotional distress (Albert et al., 2007). Decreased visual function makes the pursuit of leisure tasks difficult with the most reportedly affected activities being reading and driving. The loss of valued activities is associated with higher rates of depression (Rovner and Casten, 2002), with the prevalence of depressive disorders in people with bilateral AMD being double that of those without AMD (Brody et al.,2001). Mathew et al. (2011) found that in a study group of 249 people with moderate AMD and visual acuities of 1.00 logMAR (6/60 snellen) or better, half of the study group had significant depressive symptoms. The group had a ten times increased risk of depression compared with age-matched controls without co-morbidity. AMD sufferers were found to have reduced general health, decreased physical and social function and increased requirement for assistance to undertake daily living activities such as reading. All of these factors were linked to significantly reduced quality of life (Mathew et al 2011).

Older adults with AMD are more likely to suffer injurious falls than those without AMD (Wood et al., 2011). The fear of falling is also more prevalent in older adults with AMD, with greater levels of fear associated with more advanced levels visual impairment (Landringham et al., 2014). A fear of falling is linked to reduced social activity, limited physical activity, depressive mood and reduced quality of life scores (Wang et al., 2012, Cumming et al., 2000).

The Macular Disease Society surveyed the effect of the disease on leisure activities for its members using a postal questionnaire. Prior to diagnosis of AMD, 59% of responders enjoyed reading, however this decreased to 20% at the time of the survey. Over half of the responding participants reported a decrease in the number of hobbies since diagnosis, with reading being the most commonly limited leisure pursuit (Mitchell et al., 2002).

Vision loss affects many aspects of life, but one aspect that optometrists may be able to help with is reading. Various attempts to improve vision have been made. Currently low vision services provide valuable advice about eccentric fixation, steady eye strategies and provision of optical magnifiers. In the UK, Low Vision Services are well established and historically have been provided by optometrists within hospital eye departments. The cost of outpatient appointments and low vision devices is considerable across the UK. Electronic magnifiers are available for self-funding patients, although the high costs are prohibitive for many people.

1.3 Reading with Macular Disease

As central vision becomes more difficult to use, people with AMD spontaneously select a peripheral point outside the central macular to fixate. This 'preferred retinal locus' (PRL) is used to read (Crossland et al., 2005). The PRL is often located above an atrophic lesion, positioning the scotoma superior to fixation. Fixation stability remains unchanged by the extent of PRL eccentricity (Greenstein et al., 2008). Despite fixation stability, when using a PRL to read, mean reading speed decreases by 4% as the distance between the fovea and PRL increases by 1º (Bernard et al 2011).

It is well established that both distance and near visual acuity reduce with fixational distance from the fovea. Figure 4 shows the reduction in visual acuity with increasing eccentricity, as plotted by Lewis et al., (2011). Lewis et al. used drifting and static Gabor patches to measure visual acuity outside the fovea in healthy emmetropic eyes. Results show an increased visual acuity in the temporal visual field compared with the nasal field, however both temporal and nasal visual field have a marked decrease in visual acuity with increasing eccentricity from fixation (Lewis et al., 2011, also see Figure 7).

***Figure 4: Graph to show reducing visual acuity (VA) with increasing eccentricity**. Graph depicts mean visual acuity for static Gabor patches (SVA) and dynamic Gabor patches temporally modulated at 1º per second (DVA $1^{\circ/s}$) and 2º per second (DVA$2^{\circ/s}$) measured across the horizontal visual field (taken from Lewis et al., 2011).*

Ehsaei et al (2013) reported the nasal visual field has reduced visual acuity compared with the temporal visual field, whilst the inferior visual field has increased visual acuity compared with the superior visual field. The reduction in visual acuity with increasing eccentricity is more pronounced when testing along the vertical meridian compared with the horizontal (Ehsaei et al, 2013).

Photoreceptors in the foveal region are tightly packed and provide a high sampling frequency, with a peak foveal cone density of 199,000 cones/mm^2 (Curcio et al, 1990). The information from a single cone can be preserved in the output from the foveal region with more bipolar and ganglion cells being present than cone photoreceptors (Banks et al., 1991). The decline in cone receptor density declines asymmetrically with eccentricity, with the nasal retina having 40-45% more cones compared to the temporal retina. Ganglion cell density in the nasal retina also exceeds that in the temporal retina by 300%. These findings correspond to the improved visual acuity in the temporal visual field compared to nasal (Lewis et al, 2011 and Ehsaei et al 2013).

The increased visual acuity of the inferior field compared to the superior cannot be explained with cone receptor cell density, which is virtually symmetrical between the inferior and superior retina (Curcio et al 1990). However, the ganglion cell density of the superior retina exceeds that of the inferior retina by 60% (Curcio and Allen, 1990). Therefore, the receptive field per ganglion cell is smaller in the inferior field compared to the superior field and accounts for the improved visual acuity.

The cortical magnification factor (M) is the scale of topographical representation of the visual field within the striate cortex (mm/degree of visual angle). With the exception of foveal vision, the inverse value of the cortical magnification factor (1/M) has an approximately linear increase with retinal eccentricity. Foveal vision appears to be over-represented in the striate cortex

(Popovic and Sjostrand, 2001, Levi, Klein and Aitsebaomo, 1985, Daniel and Whitteridge, 1961, Dow, Snyder, Vautin and Bauer, 1981, Tootell at el., 1988 and Azzopardi et al., 1999).

When considering the cortical magnification factor, if AMD sufferers use a PRL to fixate, the corresponding topographic representation in the visual cortex is reduced compared to foveal fixation. Therefore target objects must be suitably enlarged as to match or surpass the threshold visual acuity required by the peripherally located retina to facilitate recognition.

The extent to which near and distance best corrected VA is reduced by AMD is an important clinical indicator as to the functional limitations caused by vision loss. Both distance and near acuity charts are widely used in low vision clinics to quantify the loss of visual acuity in AMD patients. However, because the chief complaint of AMD sufferers is the inability to read (Mitchell et al., 2002), quantifying reading ability maybe a more relevant clinical measure. One model used in clinical research to assess and determine reading ability is the ‘rate of reading curve’.

1.4 The Rate of Reading Curve

The rate of reading curve plots reading speed against print size. Reading speed is usually expressed in words per minute and is determined by recording the time taken to read a passage of known word length. If reading speed is determined for several such passages of varying print size, a rate of reading curve can be derived.

Rate of reading curves reveal three functional measures of reading performance: (i) Reading acuity, the smallest print that can just be read; (ii) Maximum reading speed, the reading speed attained when performance is not limited by print size; (iii) Critical print size (CPS), the smallest print size that supports the maximum reading speed (Mansfield and Legge, 2007).

A classic rate of reading curve is depicted in Figure 5, and shows an increase in reading speed with increasing print size up to the CPS. Beyond the CPS, reading speed does not increase further. Indeed, the rate of reading often reduces with very large print sizes (Legge et al.,1985a and 1985b).

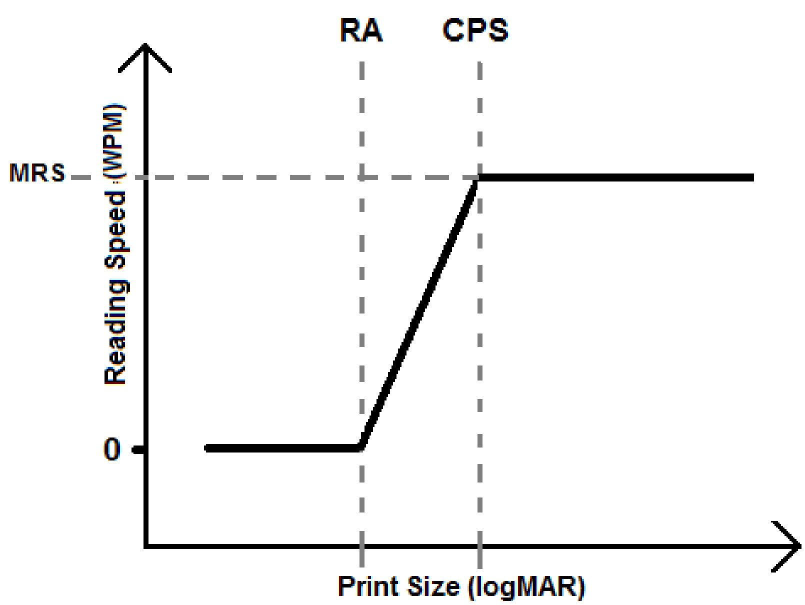

Figure 5: Rate of reading curve*. RA= reading acuity; CPS= critical print size; MRS = maximum reading speed. WPM = words per minute. See text for details.*

It is reasonable to assume that if print size is appropriately scaled to counter the loss in acuity with eccentricity, the rate of reading curve produced when using eccentric vision should be similar to that produced when using central vision. The rate of reading curve would be expected to move laterally along the x axis in response to the larger print sizes required for eccentrically viewed text, though the maximum rate of reading would be the same.

However, this is not the case. When peripheral vision is used to read, even if the print is appropriately scaled to counter the cortical magnification factor, maximum reading speed is reduced compared with central vision. This is shown in Figure 6. The rate of reading curve is moved laterally along the x axis and vertically down the y axis (Chung et al., 1998).

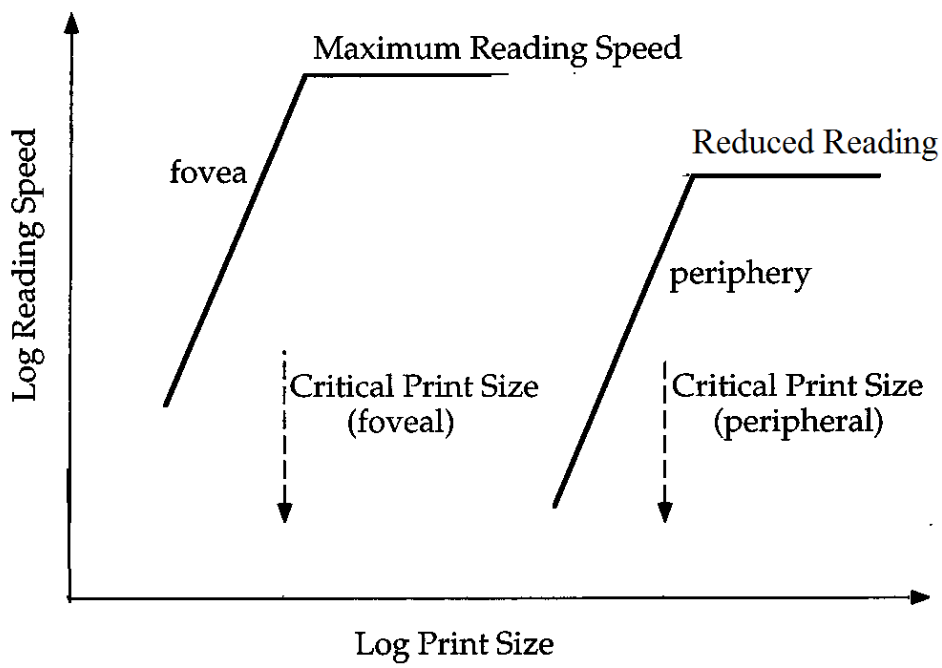

Figure 6: The rate of reading curve plotted for foveal and peripheral fixation*. The maximum reading speed is reduced when using peripheral fixation compared with foveal vision despite appropriate scaling of print. Therefore, print size cannot be the only limiting factor when reading with peripheral vision (Adapted from Chung et al.,1998).*

Legge et al. (1985b, 2007a) reported that reading speed was reduced for people with low vision compared with normal vision, even when print size was sufficiently large as to support the CPS. Measurements of average reading speeds for various groups of low vision patients were determined as: (i) intact central field and clear media – 132 wpm; (ii) intact central field and cloudy media – 95 wpm; (iii) central scotoma and clear media – 39 wpm; (iv) central scotoma and cloudy media – 28 wpm (Legge et al., 1985b, 2007a).

These findings are in agreement with Chung (1998), who quantified the reduction in reading speed as being 6 times slower when using a 20 degree eccentric fixation point compared with foveal fixation.

These results confirm that text size is not the only limiting factor when reading with peripheral vision.

1.5 Factors affecting Reading when using Peripheral Vision

1.5.1 Anatomical Factors

As discussed in section 1.4, visual acuity reduces with increasing eccentricity from foveal fixation. Retinal cell density differs between central vision and peripheral vision and many aspects of the variation in spatial vision across the visual field can be understood by analysing the spacing of photoreceptors and ganglion cell receptive field sizes (Banks et al., 1991).

Anderson et al. (1991), reported in addition to optical and receptoral properties, spatial resolution across the visual field is also limited by higher order neural properties. Figure 7 depicts spatial resolution of chromatic and achromatic stimuli decreasing into the peripheral field at a faster rate than known optical and/or receptoral properties of the human eye dictate.

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***Figure 7: Factors affecting eccentric acuity**. Achromatic and chromatic acuity declines with eccentricity from the fovea. The rate of decline is greater than that ascribed to the optical and/or receptoral properties of the human eye. Anderson et al (1991) report both achromatic and chromatic acuity are limited by post-receptoral mechanisms in human peripheral vision (Anderson et al., 1991).*

1.5.2 Saccadic Eye Movements

Reading necessarily involves saccadic eye movements and it is estimated that four fixations per second are used when reading with normal vision (Huey, 1908). If there is a central scotoma, AMD sufferers will use their PRL as the reference point from which these fixation are made. Even when this newly adopted peripheral point has become familiar to use, fixing to the appropriate part of the sentence to allow reading may be troublesome (Sunness and Applegate, 2005). Reading speed is therefore slower when using an eccentric point outside the fovea as a base from which to make saccadic eye movements (Whittaker et al., 1991).

A method known as 'Rapid Serial Visual Presentation' (RSVP) has been developed to minimise the impact of saccadic eye movements when reading with eccentric vision (Spence, 2002). Words appear on a visual display screen in successive sequence in the same spatial location. This negates the need to make saccadic eye movements across a line of text.

However, even when RSVP methods are used, peripherally fixated reading speeds are still reduced. Therefore, eye movement control alone cannot account for the reduction in reading speed for peripherally viewed text (Chung, 1998, Ruben et al., 1994).

1.5.3 Crowding in Human Vision

Crowding refers to the phenomena in which juxtaposed targets viewed eccentrically may be difficult to identify. The object of regard does not disappear, but is confused and confounded by adjacent flankers making recognition impossible (see Figure 8). When using central vision, the effect of crowding is minimal. However, it becomes increasingly potent when using peripheral vision (Bouma, 1970).

Crowding effects have been reported to occur in a wide variety of tasks including: letter recognition (Bouma, 1970, Toet and Levi, 1992), vernier acuity (Levi et al., 1985), orientation discrimination (Andriessen and Bouma, 1976), stereoacuity (Butler and Westheimer, 1978) and face recognition (Louie et al., 2007).

The orientation of flankers may affect crowding. In all four quadrants of the visual field, the effect of crowding is greater when flankers are arranged horizontally rather than vertically (Feng et al., 2007). Crowding is also more potent when multiple flankers are present compared with a single flanker (Bouma 1970).

The neural location of crowding is not known. It is thought to have a cortical locus because the effect is still present when the flanker and target are presented to different eyes, indicating that processes beyond inter-ocular interactions are involved (Levi, 2008; Flom et al., 1963).

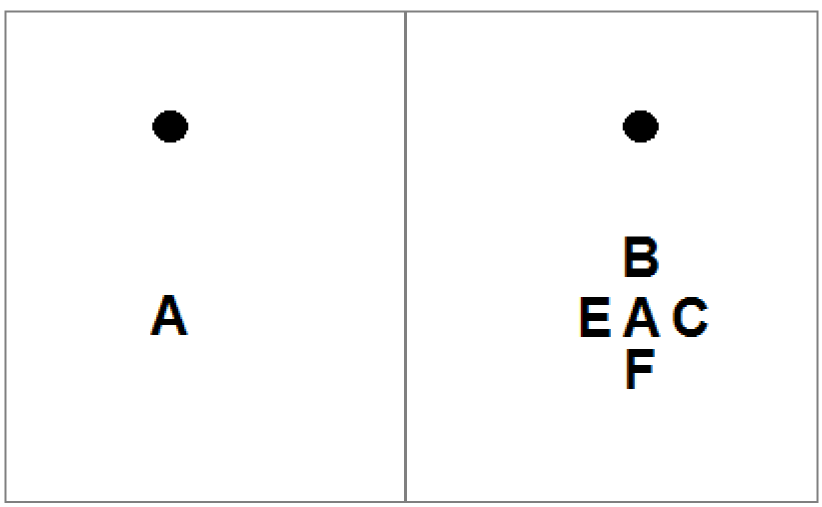

Figure 8: Example of the effects of crowding. *Fixating on the black circle in the box on the left allows recognition of the letter A. In the box on the right, when fixating on the black circle, the letter 'A' is not recognisable due to the crowding effect of the flanking letters (Image based on Bouma 1970, Levi 2002).*

Bouma studied the effects of manipulating spacing to reduce the effects of crowding when using peripheral vision. It was found that when the target and flanker were separated by a distance equal to half the retinal eccentricity, the ability to identify a target improved (Bouma, 1970).

Bouma found that crowding is a linear function of eccentricity and can be expressed as:

$$s = s_o + ɧ\phi$$

where s equals critical spacing; s_o equals critical spacing at zero eccentricity; ɧ equals Bouma's constant; and ϕ equals eccentricity.

Critical spacing is the smallest distance between target images measured centre-to-centre that is required to avoid crowding.

Bouma described critical spacing as, "*for complete visual isolation of a letter presented at an eccentricity of* ϕ*, it follows that no other letter should be present within (roughly) 0.5*ϕ *distance.'*

If Bouma's critical spacing is upheld, peripherally viewed targets should be identifiable if critical spacing is exceeded. Critical spacing depends on centre-to-centre distance and not edge-to-edge distance (Levi and Carney 2009, Pelli et al., 2004 and Levi et al., 2002).

1.5.4 Receptive and Integration Fields

Successful perception of a target involves two stages; feature detection and feature integration (Levi, 2002). Feature detection occurs in early visual cortex, with simple and complex receptive fields. Integration fields sum the detected features and correspond to an area circumscribed by the measured critical spacing around the stimuli (Pelli et al., 2004, Levi et al 1985). Integration fields are distinct from receptive fields and reflect higher cortical processes (Pelli et al., 2004 and Toet and Levi, 1991), whereupon individual features of an object or scene are combined.

If a target image and a flanking image fall within the same integration field, they cannot be discerned as separate and identification is hindered. If the target image and the flanking image fall in two different integration fields, the target image will not be affected by crowding (Levi, 2008). Integration fields in central vision are small, and become increasingly large into the peripheral field, and therefore space between target and flanking objects must be greater to allow images to fall into adjacent integration fields (Chung 2012; Toet and Levi, 1992; Pelli and Tillman, 2008). AMD sufferers using eccentric fixation to read may use inappropriately large integration fields to the detriment of accurate image perception (Pelli, 2004).

Figure 8 illustrates the effect of crowding. When the viewer is presented with a target object, for example a letter ‘A’ in isolation, it will firstly be detected by the visual system, then have its features integrated to provide the viewer with a recognisable percept. If the target letter is presented amongst flanking letters, the visual system will still attempt the two stage process of detection and integration. The letter will be detected within a receptive field, however, when integrating the features of the target letter A, the flanking letters will also be included. The perceived image is integrated with its surrounding flankers and the target letter ‘A’ will appear indistinct and jumbled (Levi, 2002).

When integrating target objects with surrounding flankers, crowding causes perceptual similarity. The target word will appear to alter its appearance and become more similar to the flanking letters; the visual stimulus of the target and flankers are pooled. This is known as the faulty integration theory (Greenwood, 2010; Parkes et al., 2001).

1.5.5 The Effect of Crowding on Reading: The Visual Span

Crowding affects both letters and words when reading. Letters and words above, below and to the side of a target word will act as flankers and reduce ability to recognise words. As with all types of crowding, the effects of crowding on reading ability increases with eccentricity (Chung, 2004).

To understand the mechanisms of reading in terms of crowding and saccadic eye movement, Bouma describes the concept of an uncrowded visual span. That is, *'in a single fixation there is a central window of uncrowded vision which we use to read, and a crowded periphery through which we cannot*,' (see Figure 9). Reading speed is proportional to this central window, which has been described as the 'uncrowded visual span' (Bouma 1970, Pelli et al., 2007). The uncrowded visual span is the number of characters that can be seen in one fixation, without the help of linguistic knowledge or content. Surrounding the uncrowded visual span are words and letters indiscernible due to crowding.

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Figure 9: The uncrowded visual span. *One fixation will allow a central window of uncrowded vision, surrounded by a crowded periphery (taken from Legge 2001).*

The usual visual span measures ten characters in length, and extends further on the right than the left for normally sighted people who habitually read from left to right (Legge et al., 2001). Words are recognised in parts and if enough of the target word falls within the uncrowded span it is likely the word will be legible to the reader.

Visual span size can vary between subjects, being larger in fast readers and smaller in slow readers (Rayner et al 2010). Interestingly, subjects who read Hebrew have a reverse visual span configuration, which extends further on the left than the right (Pollatsek et al1981).

When using a peripheral retinal locus to read, the number of letters which will fit into the visual span in one fixation decreases (Bouma, 1970, Legge, 2007b). The reduction of visual span width decreases from ten letters centrally to 2.8 letters at 15 degrees eccentricity (Legge, 1987). A smaller visual span requires an increased number of intra-word saccades to read, and therefore reading speed may be reduced (Pelli et al., 2007).

Yu et al. (2010) reported that the size of the visual span is determined by three factors: (i) resolution at a specific retinal locus; (ii) mislocation, i.e uncertainty about relative position of letters; and (iii) crowding. Of these three factors crowding was reported to be the major one.

1.6 Attempts to Improve Legibility of Peripherally Viewed Text

1.6.1 Font Style

Mansfield et al (1996) investigated the effects of font style on maximum reading speed, reading acuity and critical print size for normal and low vision participants, as measured with the MNREAD acuity charts. Courier font which has serif typeface and mono-spacing was compared to the sans serif and proportionally spaced Times New Roman font. For low vision participants, Courier font had significantly improved reading acuity, CPS and maximum reading speeds compared with Times New Roman. The relatively increased spacing and the serif typeface of Courier font may have reduced the effect of crowding and therefore promoted reading ability for low vision participants.

Later work by Tarita-Nistor et al (2013) confirmed improved reading acuity for Courier font compared to Times New Roman font for participants with central vision loss. However, results differed from Mansfield et al (1996) in that maximum reading speed and critical print size did not significantly differ between font styles tested.

Rayner et al. (2010) reported font style affected eye movement control, with mono-spaced font eliciting more forward fixations with shorter duration compared with proportionally spaced text. Overall, mono-spaced font and proportionally spaced font did not differ in reading rate or width of visual span.

1.6.2 Letter Spacing

Chung (2002) investigated the effect of increased horizontal letter spacing on reading speed. Reading speed of words presented by RSVP techniques were measured for normally sighted observers with intra-word spacing ranging from x0.5 -x 2 standard spacing. For centrally and peripherally viewed text, reading speed did not benefit from increased letter spacing beyond the standard value (see figure 10). This finding was repeated in a later paper using participants with central vision loss (Chung 2012).

The lack of effect of increased letter spacing demonstrated in Chung's 2002 paper may be because any advantage gained by minimizing the effects of letter crowding were negated by a reduction in word shape information and/or visual span, factors known to be critical for efficient reading (Slattery and Rayner 2013, Pelli and Tillman, 2008; Chung, 2002; Legge et al., 2001; Cohen 2008).

Paterson et al. (2010) found increasing spacing between letters within a word negatively affected eye movement control, causing subjects to use more fixations and longer saccades when reading text. However, the reduced reading speed caused by increasing letter spacing was not catastrophic and subjects could adapt to the typography style so long as word boundary information was available in the form of increased inter-word spacing.

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Figure 10: Effects of increased letter spacing on reading speed using eccentric fixation of normally sighted observers. *Chung et al. (2002; 2012) reported reading speed did not benefit from increased intra-word spacing past standard spacing for print 0.8CPS or 1.5CPS tested at foveal, 5º and 10º eccentric fixations. This was the case for both simulated and genuine macular scotomas. Below the standard spacing, reading speeds reduced (taken from Chung et al., 2002).*

1.6.3 Word Spacing

Drieghe et al. (2005) investigated the effect of word spacing on reading ability by measuring the fixation duration of normally sighted individuals reading sentences displayed on a monitor. Double word spacing was found to have reduced fixation duration and faster word recognition compared with single word spacing. This was presumed to be due to reduced lateral masking. It was also found that the duration of foveal word fixation reduced when the subsequent word in the target sentence was a 'long word' of 8 letters in length (Dreighe et al 2005).

Rayner et al. (2010) reported that the reduced reading speed caused by reducing intra-word spacing by 10% could be outweighed by increased word spacing. The inhibitory effects of increased lateral crowding and disrupted word identification processes for text with reduced intra-word spacing were offset by increased exterior word boundary demarcation (Rayner et al 2010, Slattery and Rayner, 2013).

1.6.4 Vertical Line Spacing

Chung (2004) investigated the effect of line spacing on reading speed when using central and peripheral vision in normal observers. Using the method of RSVP, Chung measured the reading speed of unrelated words when vertical line spacing of flanking words was manipulated. Increasing line spacing was beneficial to both centrally and peripherally viewed words, with a relatively greater increase in reading speed for peripherally viewed text (see figure 11).

A later study by Chung (2008) attempted to replicate the beneficial effect of increased vertical line spacing using participants with genuine central vision loss secondary to AMD. However, the beneficial effect of increased word spacing Chung observed in normal subjects was not evident in AMD patients. This result was true when using both unrelated words and coherent sentences. These contradictory results may have been affected by the small study size (n = 4) and the use of RSVP, which is not comparable with everyday reading tasks.

Bernard et al. (2007) also assessed the effects of increased line spacing when reading with a central scotoma. A small cohort of seven participants with simulated central scotomas showed only a modest increase in reading speed of 26% gain for 178% increase in line spacing when using French adapted MNREAD charts. Reading speed was more dependent on print size, perceptual learning and scotoma size than line spacing (Bernard et al., 2007).

The French adapted MNREAD charts were again used to investigate the effect of vertical line spacing on reading speed by Calabrese et al (2010), using participants with genuine central vision loss. This study found a significant, albeit modest improvement to reading speed of 7.1 words per minute when line spacing was increased from singe to double spacing. This increase was found to be independent of scotoma size.

1.6.5 Visual Rehabilitation

Visual rehabilitation has been used to increase readability of peripherally viewed text by teaching strategies that utilise remaining vision. Spiele et al (2011) compared the relative effectiveness of training modules which aimed to improve reading ability of AMD sufferers over a six week period. PRL training and reading practice without eye movement did not improve reading speed. However, oculomotor training improved reading speed by 27%. This is in close agreement to Spiele's earlier work (2005) where eye movement training increased reading speed by 27.5% in a group of AMD sufferers.

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Illustration removed for copyright restrictions

Figure 11: Effect of increased line spacing on reading speed using eccentric fixation of normally sighted observers. Chung (2004) reported an increase in reading speed for observers with simulated central scotomas when vertical line spacing increased to x2 standard spacing. This was more marked for eccentric fixation than central (taken from Chung, 2004).

1.7 Aims

The principal aim of this thesis was to investigate the effect of typography, and in particular text spacing, on the reading ability of both normally-sighted observers and AMD patients with central vision loss.

Firstly, preliminary measures (see section 2.0) were made on normally sighted observers using eccentric fixation to investigate the effect of text size, font style, word spacing and line spacing on reading ability. The results from these preliminary measures were used to derive an appropriate search space, in terms of text spacing, for assessing reading performance in AMD patients.

Secondly, experimental measures on AMD patients (see section 4.0) were completed to assess the effect of word and line spacing on reading speed for both full and reduced contrast text. The reduced contrast text was used to increase the difficulty of the test, thereby providing a more sensitive measure of reading performance. Also, the reduced contrast text was used to mimic a possible reduction in letter contrast in subjects with central visual opacities.

The results of all experiments were compiled to produce guidelines for the optimal textual layout for AMD patients.

Preliminary Measures on Normally-Sighted Observers

2.0. Preliminary Measures: Experimental Measures on Normally-Sighted Observers

2.1 Introduction

The aim of this preliminary study was to assess the effects of crowding on reading performance using normal peripheral vision to determine a suitable textual parameter search space for the main clinical trial. The search space will be defined in terms of the required word and line spacing that will be tested in the clinical trials using AMD patients (see section 4.0). The approach adopted here differed from previous studies in two ways. First, whole sentences were used to allow saccadic eye movements that model closely the normal reading process. Second, forced-choice psychophysical procedures were used to assess reading performance. The procedure was based on a paradigm introduced by Dakin and Morgan (1999), whereby each observer's ability to evaluate a statement as true or false was measured as a function of exposure time. A psychometric function relating the proportion of correctly evaluated statements to exposure time was derived for each parameter (e.g. font type, text size, word and line space), with threshold exposure time defined as that which yielded 75% correct performance.

2.2 Methods

Stimuli

Short, mathematical statements were displayed on a Sony GDMF520 monitor at a frame rate of 100 Hz using a Cambridge Research Systems (CRS) VSG2/5 graphics card. Eight statement categories were used and they are listed in Table 1, together with examples of true and false statements for each category.

Times New Roman (TNR) and Lucida Sans (LS) proprietary Microsoft True Type fonts were used. Other parameters varied included text size (defined as the visual angle subtended by a lower-case 'x'), horizontal word spacing and vertical line spacing. Word spacing was varied using standard character (space-bar) spacing for each font. Line spacing was varied in multiples of the height of an upper-case ‘X’ for each font. At a viewing distance of 40cm, text size was 0.55-1.93^{o}. To minimize the deleterious effects of light scatter with display monitors, experiments were completed using white letters (70 cd/m^{2}) on a black background (0.1 cd/m^{2}).

Target statements were presented at a retinal eccentricity of 5^{o} in the superior field, and each was read by saccading along a fixation line. Eccentricity was measured as the vertical distance from the fixation line, which extended across the monitor and was present throughout all trials, to the centre of the statement (defined as the centre of the *x-height*). Each statement was presented either in isolation or with flanking text positioned symmetrically above and below it. The first word of each statement was positioned 1cm from the left-hand edge of the monitor. Eye movements, recorded offline for observer SJA using the CRS Video EyeTracker Toolbox, showed that deviations from the fixation line were less than 0.5 deg and did not vary from one condition to another. Eye movements were not monitored for observer SB. However, SB underwent several fixation control practice sessions prior to commencing each set of experimental trials.

Statement category	True statement	False statement
Multiplication	one times nine equals nine	two times three equals four
Addition	four plus four equals eight	four plus three equals five
Subtraction	fifteen minus six equals nine	six minus three equals two
Division	ten divided by two equals five	nine divided by two equals one
Comparison	eight is greater than six	nine is smaller than six
Sign-evaluation	seven minus nine is negative	four minus seven is positive
Even/odd-determination	three is an odd number	eight is an odd number
Polygon-determination	a rectangle has four sides	a pentagon has three sides

Table 1: Examples of statements used in preliminary trials. *Examples of the true and false mathematical statements (target and flanking) used to assess reading performance. Each statement consisted of either five or six words.*

2.3 Procedure

Detection thresholds were determined separately for each parameter set. A binary-choice procedure was used in conjunction with the method of constant stimuli to measure psychometric functions relating reading performance for correctly evaluating target statements as a function of presentation time (range 50-2500ms). Each datum was calculated as the proportion of correct responses from a minimum of 25 trials. Each trial was initiated by a button press and consisted of a single-interval presentation of the target statement, which was evaluated in silence and recorded as true or false by depressing either the right (true) or left (false) button on a response box. An incorrect response was signaled by an audible tone. Following this judgment, for which no response deadline was imposed, observers re-fixated the start of the line near the left-hand edge of the monitor before initiating the next trial, which began 2s after depressing another button on the response box. On each trial, target and flanking text was selected at random from a total of 320 different statements (20 true and 20 false statements in each category). The criterion for threshold was set at 75% correct performance. Viewing was binocular.

2.4 Observers

SBW and SJA acted as observers for all experiments. SBW (aged 28 yrs) had normal visual fields an 6/6 unaided Snellen acuity. SJA (aged 56 years) had normal visual fields and 6/6 corrected Snellen Acuity. The study was approved by the Aston ethics committee and adhered to the tenets of the Declaration of Helsinki.

2.5 Results and Discussion

2.5.1 Normally-Sighted Observers: Effects of Font Type and Size.

Psychometric functions relating the proportion of correct responses to presentation time were measured for various text sizes. Figure 12 shows, for target statements presented without flanking text, a sample of the functions for both Times New Roman and Lucida Sans fonts. The solid curves through each data set show the fit of a two-parameter (threshold, slope) Weibull function, which was made using a maximum-likelihood method of parameter estimation (Wichmann and Hill, 2001a and 2001b). For observer SJA, for each font size used (see figure 12, panels d-f), performance rose from chance (50%) to near perfect as presentation time increased. For observer SB-W, performance rose above chance with increasing presentation time for all but the smallest font size used (see Figure 12, panels a-c; for complete raw data set see appendix 1).

To assess the reliability of the estimated thresholds, a parametric bootstrap-based procedure was used to derive the 95% confidence intervals (Winchmann and Hill 2000b). Goodness-of-fit tests were made using a deviance measure that assessed both over- and under-dispersion (Winchmann and Hill 2000a). An example of this approach is shown in Fig. 13 for a Lucida Sans font of size 1.49^{o}. The solid curve in Fig. 13a shows the maximum-likelihood Weibull function fit to the data. Figure 13b shows the Monte-Carlo generated (bootstrap) threshold distribution for this data set: the detection threshold (959ms) and 95% confidence interval (684-1211ms) are marked on the abscissa. Figure 13c shows the deviance distribution: the fitted function is deemed acceptable because the deviance score (4.7) lies well within the confidence interval (1.7-14.8) (Winchmann and Hill 2000a). Note that this was the case for more than 97% of the functions fitted.

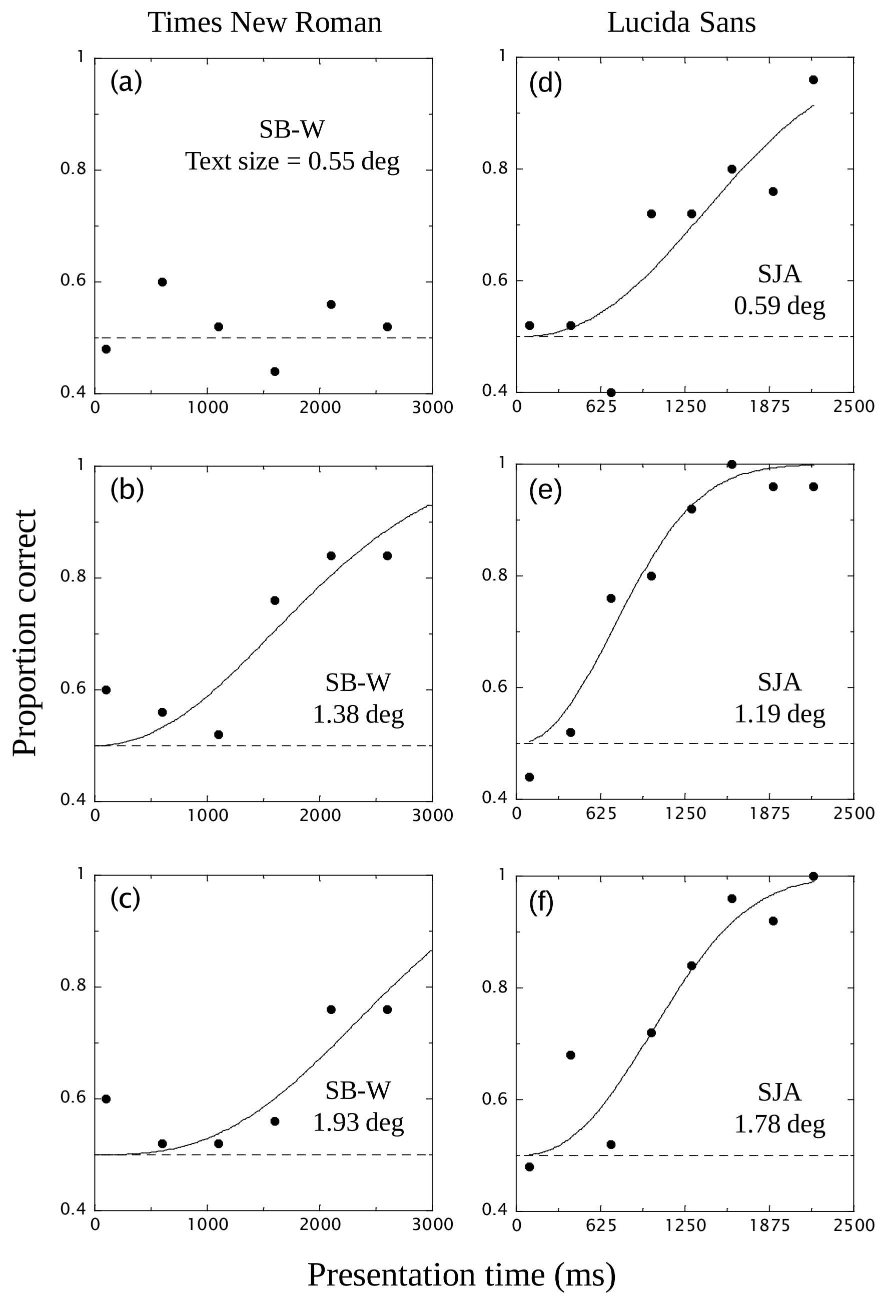

Figure 12: Threshold performances for text sizes varying from 0.55-1.93 degrees. *Sample of the raw data, plotted as psychometric functions of reading performance (proportion of correct responses) against statement presentation time (ms). The horizontal broken line in each panel indicates chance (50%) performance. Data is for plain target statements presented in isolation. The solid curves show a maximum-likelihood Weibull fit to each data set (Wichmann and Hill, 2001a, b). Performance increased from chance to supra-threshold levels as presentation time increased for all print sizes except 0.55 degrees.*

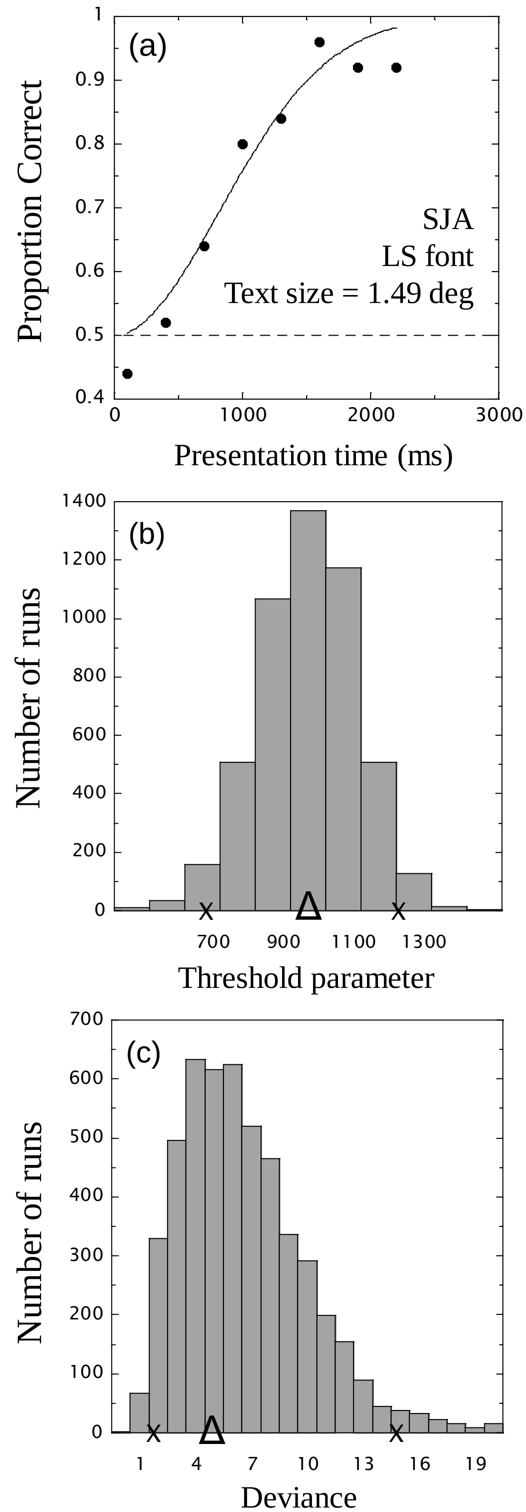
(a)
SJA
LS font
Text size = 1.49 deg
Proportion Correct
Presentation time (ms)
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1000
2000
3000
(b)
Number of runs
Threshold parameter
0
200
400
600
800
1000
1200
1400
700
900
1100
1300
(c)
Number of runs
Deviance
0
100
200
300
400
500
600
700
1
4
7
10
13
16
19

Figure 13

Figure 13: Statistical analysis of psychometric data. *Sample case detailing the statistical analyses employed to assess the variability of the fitted functions and their goodness-of-fit, based on Winchmann and Hill (2001a, 2001b) and implemented by software written by M.A. Georgeson. (a) Psychometric function of reading performance (proportion of correct responses) against statement presentation time (ms) for observer SJA, using a Lucida Sans font of size 1.49^o. All data were collected for target statements presented without flanking text. As in Fig. 1, the solid curve through the data shows the fit of a Weibull function, and the broken line indicates chance performance. (b) Binned histogram showing the Monte-Carlo generated threshold distribution for the fitted function, based on 5000 synthetic data sets. The detection threshold (open triangle: 959 ms) and 95% confidence interval (crosses: 684 – 1211 ms) are marked on the abscissa. (c) Binned histogram showing the Monte-Carlo generated deviance distribution: the deviance score (open triangle: 4.7) and 95% confidence interval (crosses: 1.7 – 14.8) are marked on the abscissa.*

Following conventional practice, the 95% confidence intervals are used and displayed in the summary figures that follow (Figs. 14 – 16). Note, however, that the overlap of 95% confidence intervals to compare response thresholds across experimental conditions is too conservative for a test of significance at the 0.05 level. Payton et al. (2003) demonstrated that, when using confidence intervals to test hypotheses, the 84% intervals will approximate a test with $\alpha = 0.05$. Therefore, in the following summary figures, all significant differences noted between conditions are based on the overlap of 84% confidence intervals (denoted as CI_{84}).

Figure 14 shows the detection thresholds for correctly evaluating target statements plotted as a function of text size. For both Lucida Sans and Times New Roman fonts, a significant improvement in performance (i.e. reduction in detection threshold) occurred when text size increased to about 0.85^{o} ($p < 0.05$, CI_{84}). With further increases in text size, reading performance with the Times New Roman font remained steady while that for the Lucida Sans font began to decline. These results are in close agreement with those derived using rapid serial visual presentation to estimate critical print size for reading eccentrically-viewed text (Chung et al., 1998, Chung 2004, Pelli et al., 2007), and suggest that a text size of at least 0.85^{o} is appropriate when reading at 5^{o} eccentricity.

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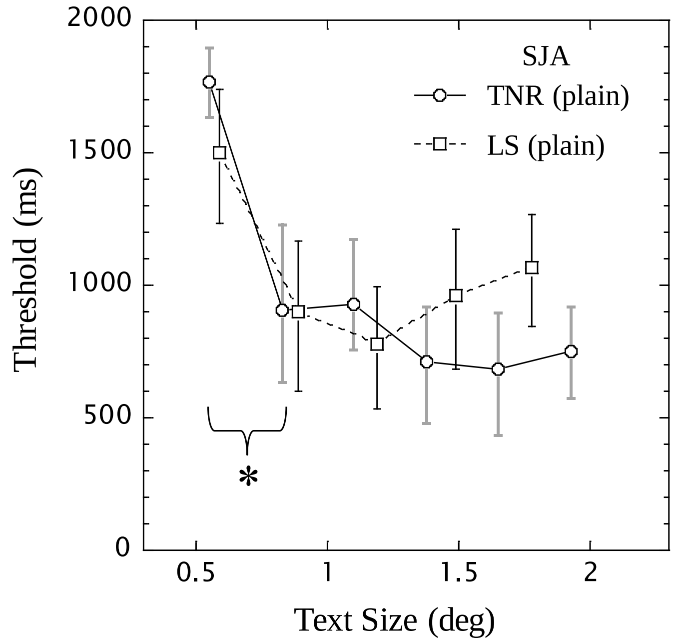


Figure 14. Summary plot: Threshold time values for tested font sizes. *Detection thresholds (ms), each derived from psychometric functions relating reading performance to statement presentation time (see Fig. 12 for examples), plotted as a function of text size. Threshold time (ms) to attain 75% correct responses shown for TNR and LS fonts are plotted for observer SJA. The asterisk (*) indicates a significant difference in the detection thresholds between text sizes of approximately 0.5º and 0.85º for both TNR and LS font types ($p < 0.05$, CI_{84}).*

2.5.2 Normally Sighted Observers: Effects of Word Spacing.

The effect of word spacing was assessed using a Times New Roman font, with target sentences presented in isolation. The font size was 0.83^{o} for observer SJA and 1.1^{o} for SB-W. These parameters were chosen because they allowed us to display each statement type across the monitor with exaggerated word spacing, and because a text size of 0.83^{o} – 1.1^{o} was near optimal for reading at 5^{o} in the superior field (see Figure. 14). Figure 15 shows the detection thresholds, derived from full psychometric functions, for word spaces from 1-3 characters. Both quantitative and qualitative differences were observed. For observer SJA, there was no significant change in performance with increasing word space ($p > 0.05$, CI_{84}). For observer SB-W, however, performance improved significantly as word space was increased from 1-2 characters ($p < 0.05$, CI_{84}). Although consistent with indirect evidence that word spacing may affect reading speed (Dreighe et al., 2005, Rayner et al., 2010, Slattery and Rayner, 2013), these results provide only modest support for the hypothesis that exaggerated word spacing is advantageous for eccentrically-viewed text.

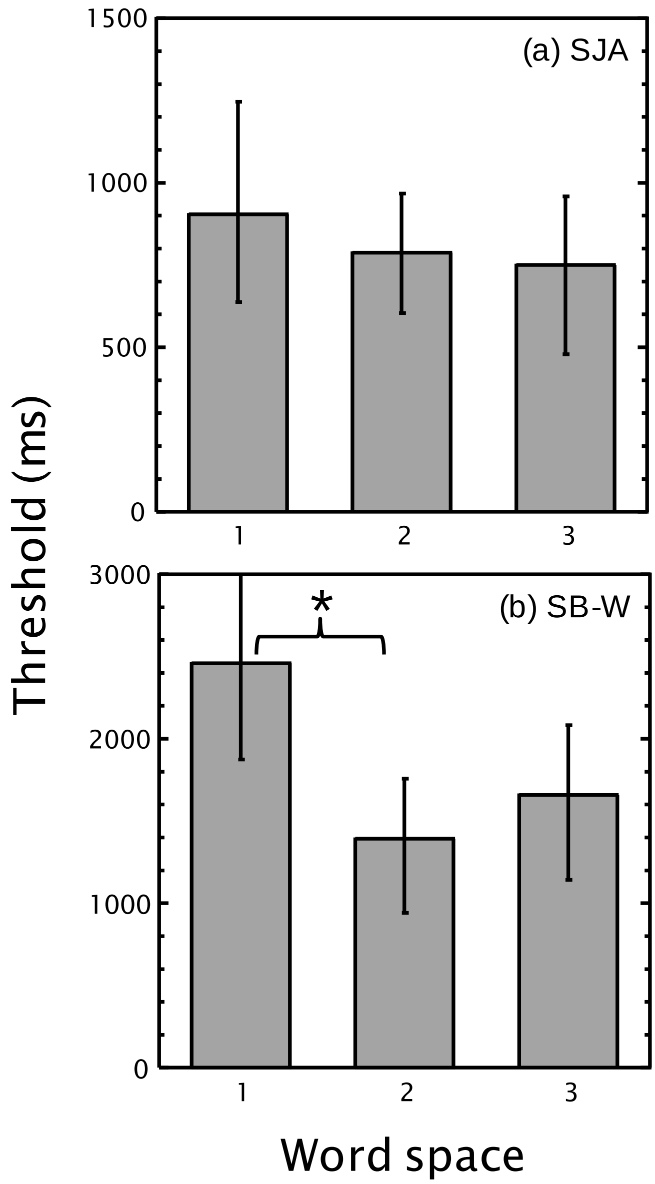


Figure 15: Summary graph: Detection thresholds (ms) plotted as a function of word space (range 1 – 3 spaces) for SJA (a) and SB-W (b). *All data was obtained for unbolded target statements presented in isolation (i.e. without flanking text) using a TNR font size 0.83 degrees (a) or 1.1 degrees (b).* The error bars show the 95% confidence intervals. Significant differences between experimental conditions are indicated by an asterisk (p < 0.05, CI84).

2.5.3. Normally Sighted Observers: Effects of Line Spacing.

Reading performance was assessed with flanking sentences positioned above and below the target sentence. All sentences were displayed using single word spacing and Times New Roman font. The font size was either 0.83^{o} (SJA) or 1.1^{o} (SB-W). The results for each observer were qualitatively similar, and are shown in Figure 16 for target sentences presented either in isolation (diagonal striped bar) or with flanking text (solid grey bars). Note that, for observer SJA, the presence of flanking text significantly reduced performance with single line spacing ($p < 0.05$, CI_{84}) but had little effect with double line spacing ($p > 0.05$, CI_{84}). The results were more pronounced for observer SB-W: she was not able to complete the task with single line spacing (i.e. threshold performance was not reached for the display times used), whereas double line spacing had no effect on performance. In general agreement with predictions from single word recognition tasks on normally-sighted observers (Chung 2004), it is concluded that exaggerated line spacing is advantageous for reading with peripheral vision.

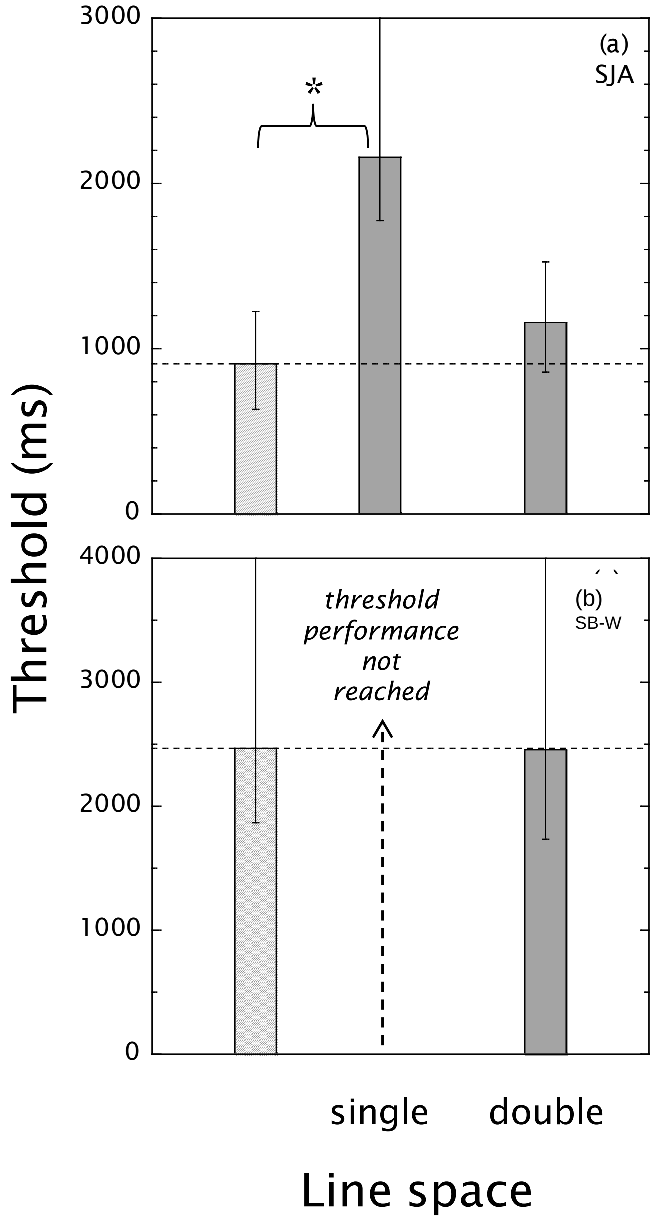


***Figure 16: Summary plot: Line spacing**. Detection thresholds (ms) for evaluating a target statement when presented either in isolation or with flanking text lines above and below target line. All data were obtained using unbolded (target and flanking) statements, single word spacing, and a TNR font size 0.83 degrees(a) or 1.1 degrees (b). The error bars show the 95% confidence limits. Performance for single line spacing for observer SB-W (b) did not exceed chance.*

2.6 Conclusion

In this preliminary study the effects of visual crowding on the ability of two normally-sighted individuals to read whole sentences using their peripheral vision was assessed. The use of whole sentences and free saccadic eye movements simulated a more realistic everyday reading task compared with previous studies that employed RSVP.

This report provides two indicators as to the textural search space required for the main clinical trials on AMD patients. First, double line spacing was advantageous over single spacing, and closely approximated unflanked reading speeds (Fig. 16). Second, a doubling of word space improved performance for both observers, though the improvement only reached significance for observer S-BW (Fig. 15). For both observers, there was no significant improvement on reading ability when word space was increased from double to triple spacing.

After consideration of the results from section 2.0, an appropriate search space for the clinical trials on AMD patients was deemed to be single, double and triple word and line spacing. All permutations within this search space will be employed

The LS and TNR fonts both reached threshold levels at 0.85^{o}, after which the LS font showed a reduction in threshold with increasing font size. To ensure consistency of results and avoid reading ability being affected by font style at text sizes above threshold, the TNR font was used in all clinical trials on AMD patients. TNR is a proportionally spaced font which is commonly found in everyday reading materials.

These suggestions are offered with two caveats. First, the text size and spacing needed for efficient reading may vary at different eccentricities, though the general principals should hold at all eccentricities. Second, all measures were completed on a healthy adult retina and may therefore not be directly applicable to patients with central visual loss. However, patients with macular disease do not usually exhibit significant changes in peripheral retinal function (Holopigian et al., 1997; Sunness et al., 1985). Certainly it is the case that peripheral crowding exists in both normally-sighted individuals (Pelli et al., 2004) and patients with central visual loss (Chung, 2004; Latham and Whitaker, 1996). In this respect, the dictate about the need for text spacing greater than that typically used in printed matter should be equally valid for both normally-sighted observers and macular disease patients.

Experimental Measures on Observers with Macular Degeneration

3.0 Experimental Measures on Observers with Macular Degeneration.

The studies on AMD patients used two types of near vision test charts to assess reading performance. First, a modified MNREAD test was used to determine high and low contrast critical print size and reading acuity for each participant. Second, a new test designed specifically for this project was used to measure reading speeds for a variety of word and line spacings with both high and low contrast stimuli. This new test was named the Equal Readabilty Passages (ERP) test. The General Methods chapter (see section 4.0) will outline how the tests were implemented. Here, the design concept of the MNREAD and ERP cards will be described.

3.1 Development of the Test Charts

3.1.1 MNREAD Acuity Charts

Originally designed and developed by the Minnesota Laboratory for Low-Vision Research, the MNREAD test is used to assess the effect of print size on reading speed for normal and low vision patients. MNREAD testing provides a functional measure of near vision (Mansfield and Legge 2007).

The MNREAD acuity charts consist of nineteen short sentences which are read aloud by the observer. Difficulty of the test increases as the observer continues to read, with each successive sentence being 0.1 logMAR smaller than the previous. The time taken to read each sentence is measured to the nearest 0.1second and the number of errors made per sentence is recorded. With each of the sentences having equal number of characters and the same spatial layout, any change to reading speed between sentences are primarily due to the change in print size (Mansfield and Legge 2007).

From Mansfield et al. (1994), data collected from testing with the MNREAD acuity cards allows measurement of:

a) **Reading acuity** - a measure of the smallest print size that can just be read without making significant errors.

   Acuity = smallest print size attempted + (word errors X 0.01)

b) **Critical print size** - the smallest print size that can uphold the maximum reading speed

c) **Maximum reading speed** - the maximum reading speed attainable when the reader is not inhibited by print size. Reading speed (wpm) = 60 X (10- errors) / (time in seconds)

MNREAD acuity charts use proportionally spaced Times New Roman font with black letters on a white background, providing a Michelson contrast in excess of 85%. The words used to create the sentences are those found commonly in educational material aimed at 7-9 year olds.

When used at the recommended viewing distance of 40cm, print size will vary from 1.3 to -0.5logMAR. To calculate this, the height of a lower-case letter 'x' is measured and used in the equation:

Log_{10}[(angle subtended by x-height)/(5 arc min)]

Each MNREAD sentence consists of 60 characters, including the spacing between words. The charts were designed using the assumption that a standard word consists of 6 letters including the space at the end. If this assumption is correct, each sentence of 60 characters can be divided into ten smaller parts, each representing one word. Each word on the MNREAD acuity charts has a value of 0.01logMAR. The sentences are printed onto three lines. The middle line of text attempts to mimic the vertical crowding effects that standard reading material would contain (Mansfield et al., 1994).

Submaranian et al (2009) investigated the coefficients of repeatability for the MNREAD acuity charts using low vision participants, who in the majority had reduced vision due to central vision loss. Measured reading acuity and reading speed were both found to have good levels of repeatability (repeatability coefficients of ± 0.10 logMAR). Critical print size was less repeatable at ±0.20 logMAR. However, this was accounted for by considering CPS is measured in 0.1logMAR increments rather than the more refined 0.01logMAR increments used to measure reading acuity and reading speed.

For the purposes of the current study, critical print size was measured as the smallest print size that supported a reading speed of at least 80% of the participant's maximal reading speed, where the latter was defined as the single fastest reading speed across the range of print sizes (Patel et al., 2011). Only participants with a critical print size of at least 0.8 logMAR (N20) for both low (17.5%) and high contrast (87.5%) charts were selected to take part in the full study.

3.1.2 Modifications of the MNREAD acuity chart

This study modified the MNREAD testing procedure in two ways. Firstly, the test was presented once in its original format to measure CPS of full contrast print (87.5% contrast Michelson definition), and secondly in a reduced contrast format to determine CPS for reduced contrast text (17.5% Michelson contrast). The full and reduced contrast MNREAD charts contained different sentences, which corresponded to 'chart 1' and 'chart 2'.

3.2 Development of the Equal Readability Passages (ERP) Test Cards

This study required a reading test that measured the effect of word and line spacing for whole sentences for high and low contrasts. No such test is commercially available and therefore the ERP test was developed. The ERP test cards were designed giving consideration to the following:

- content of the text was required to reflect reading material AMD sufferers may attempt to read in everyday situations.
- comprehension level must be consistent and of a suitably low comprehension level to ensure reading speed is not affected by aptitude or participant reading ability.
- font size must be suitably large to support the participants critical print size but sufficiently small to fit a passage of spaced text onto an A4 reading card.
- font style must be consistent across all test charts and be representative of font style used in everyday reading material.

After consideration of the preliminary measures completed in section 2.0, to ensure word and line spacing were comprehensively investigated, single, double and triple word and line spacing were incorporated into the ERP card design. Therefore 9 different test cards were required to test all combinations of word and line spacing.

3.2.1 Content of the ERP Test Cards

The passages of text used for the ERP test charts required content that mimicked standard reading material. Narrative sentences that described a familiar and recognisable topic were considered. Popular text such as nursery rhymes, poems and well known stories were unsuitable because participants may predict the words rather than processing through visual recognition. Instead, original passages of text were composed by SBW. The content of the sentences are shown in Appendix 1, with the passages having an aquatic theme, referring to sharks, penguins, crocodiles, seahorses, turtles, oceans, dolphins, coral and whales.

3.2.2 Comprehension of the ERP Test Cards

The Gunning Fog Index was used to ensure consistent comprehension levels between ERP cards. This index is a method of measuring the comprehension level of written English. Text is scored according to the number of educational years required to understand the text on first-time reading. The index uses the number of sentences and the number of 'difficult' words with more than two syllables per 100 words to calculate a Gunning Fog Score. Words that are proper nouns, compound words or words that have more than two syllables due to a common suffix ending such as –ed, -ing and –es are discounted as difficult words (Gunning, 1968).

$$GF = 0.4\left(\left(\frac{\text{words}}{\text{sentences}}\right) + 100\left(\frac{\text{complex words}}{\text{words}}\right)\right)$$

***Figure 17: Gunning Fog index score.**. The index score was calculated for each ERP chart text passage using the above equation. GF= Gunning Fog*

The index provides a reading level in terms of the American school grading system. For example, a score of 12 corresponds to the reading level expected from a 12^{th} grade high school senior. To convert the score into a British equivalent, five is added to the high school grade to provide the age in years of a person undergoing standard education in the UK with similar reading ability.

For text to be understood by the majority of the population, a score of 12 is required. If the text needs to be understood universally a score of 9 is recommended (Gunning, 1974, Bond and Wong 1999).

The text passages on the ERP test cards each contained three sentences, 51 words and 3 complex words. This gave a Gunning-Fog Index score of 9.1 (see appendix 2).

3.2.3 Number of words

Each ERP test card contained 51 words. This number of words allowed: (i) a complete passage to be printed onto a single A4 chart when using the greatest text spacing of triple line and triple word; and (ii) sufficiently long passages to increase accuracy of recorded reading times. With longer reading times, human error in starting and stopping the stopwatch represent a smaller percentage of the overall reading time.

3.2.4 Contrast

To closely match the contrast of the MNREAD test charts used, the ERP test cards were produced in high contrast black on white print which provided a contrast of 87.5% (Michelson's definition). Next, a duplicate set of low contrast cards were produced with a Michelson letter contrast of 17.5%. The low contrast cards were used in an attempt to avoid any potential ceiling effects, and also to mimic a possible reduction in letter contrast with light scatter from media opacities. The white sections of the cards were presented at a luminance of 100cd/m^2, produced by both fluorescent overhead room lighting and a 'daylight' angle poise lamp.

3.2.5 Font Style and Size

The ERP test cards used a Times New Roman font to match the MNREAD chart. Times New Roman font equal to 0.8logMAR was the largest print that could be printed onto a single A4 sized piece of card allowing for 51 words using triple line and triple word spacing. Therefore participants required a critical print size of at least 0.8logMAR for both full and reduced contrast MNREAD tests to proceed to testing with the ERP cards.

Exact dimensions of the text spacing used on the ERP cards are reported in Appendix 2.

3.3 Method for using ERP Test Charts

Participants wore a binocular near refraction focused for 40cm. The ERP test cards were placed on a reading stand in front of the participant, who was comfortably seated. The test was equally illuminated with no obvious glare or shadow. ERP test cards were placed on the reading stand covered with a blank card to avoid reading prior to testing.

Each observer was given a standard instruction:

"When I say start please read the passage aloud as quickly as you can without making errors. If you do make an error, or realise that you have missed a word, continue to read to the end of the passage."

The examiner (SB-W) uncovered the test card and said 'go', starting the stop watch immediately and stopping it after the participant read the last word of the last sentence. Reading speed was computed as the number of correctly-read words per minute (wpm). The number of words read incorrectly or omitted was also recorded. This process was repeated for each of the nine ERP test cards. The order in which the cards were presented was determined by a random number generator.

Data collected for each ERP test card was used to determine reading speed (wpm) for each participant using the equation:

$$\text{Reading speed (wpm)} = \frac{\text{Time taken}}{\text{(Total number of words- errors)}}$$

3.4 Examiner Bias

When measuring the time taken to read both the MNREAD and ERP test cards, the examiner started the stopwatch when the observer began to read the target text, and stopped the stopwatch when text was completed. Measuring reading time in this manner may include the delayed reaction time of the observer. By using only one experienced examiner, the delay time should be minimal and consistent between trials.

4.0 Experimental Measures

A participant group of twenty-four adults with bilateral macular degeneration were recruited to participate in the study. Part I of the study used standard optometric procedures to measure best corrected monocular distance visual acuity, best corrected binocular distance visual acuity, near reading acuity and near critical print size for high contrast and low contrast print. The participants qualified for part II of the study if high and low contrast critical print size was 0.8 logMAR or better.

Part II required the participant to read aloud Equal Readability Passages (ERP) cards, which were designed specifically for this study. The cards were equal in word length, comprehension level and font design, but varied in line and word spacing. The design of the test stimuli is outlined in detail in Section 3.0.

4.1 General Procedure

Potential participants who were attending a hospital outpatients department were identified by SB-W. Participation was discussed with the patient at the end of their routine retinal appointment. The first twenty-four patients who met inclusion criteria and were keen to participate in the study were invited to do so.

Patients were given a verbal overview of the study and provided with a letter of invitation, a patient information sheet and a consent form (see appendix 3-5). Sufficient time to read and contemplate the contents was given and the patient was encouraged to discuss their participation with relatives or friends.

The verbal explanation of the study was similar to:

"I would like to invite you to participate in a research study. This is a research study supporting my doctoral studies at Aston University. We are interested to see how altering the spacing between words and lines of text affects reading speed for people with macular degeneration.

You do not have to agree to participate in this study. If you do not wish to participate, it will not affect your treatment within the eye department in anyway. However, if you do agree to participate, your help and assistance will be gratefully received. Although there is no financial reward for participating, we hope your results will provide increased understanding of how best to present text for patients with macular degeneration."

If the patient was keen to become a participant, they were thanked for their interest and advised to take all documentation home to read at their leisure. An appointment to perform the clinical trials was made to coincide with the participants' next hospital visit.

On the next appointment, if the participant was still keen to continue, the consent form was signed, with a copy being given to the participant and the original retained by SB-W. A participant number was allocated and from this time onwards all data recorded for the participant was labelled only with this participant number to ensure anonymity.

4.1.1 Part I

Distance Acuity

The best-corrected visual acuity was measured for each eye separately and then binocularly using the 4m EDTRS chart. Acuity was recorded in logMAR units.

The EDTRS chart had four different charts, marked R, 1, 2 and 3, each with different sequences of letters. The R chart was used when refracting the right and left eye. Chart 1 was used to measure best corrected visual acuity for the right eye, chart 2 for the left and chart 3 for binocular measures. Charts were altered in this way to minimise the chance of memorising letters and falsely inflating acuity.

Near Acuity

MNREAD charts were used to measure binocular reading acuity and critical print size for high contrast text and low contrast text. A binocular add of +2.50 was used to provide a near working distance of 40cm.

The MNREAD charts were placed on a reading stand and illuminated evenly using a 'daylight' angle poise lamp, in such a way that no shadows or glare were obvious to the examiner.

SB-W concealed the printed passages on the MNREAD chart with a plain card while the test was explained using the standard verbal instructions, *"When I say 'start' please read the sentences aloud as quickly as you can without making errors. If you do make an error, or realise that you have missed a word, continue to read to the end of the sentence. You can then go back to correct yourself if you wish."*

Time taken to read to the end of the passage was recorded to the nearest 0.1 second using a stopwatch. The number of words read incorrectly or omitted was recorded.

The test continued in this manner using passages of successively smaller print size. The transition from reading fluently to being unable to read small print occurred quickly, usually over one or two sentences.

Once all MNREAD results had been collected using high contrast text, the MNREAD test was repeated using the reduced contrast charts.

4.1.2 Part II

Part II of the study involved reading 18 ERP test cards, 9 with high-contrast letters and 9 with low-contrast letters. The ERP test cards were designed specifically for this study and their development is described more fully in Section 3.0.

The high contrast ERP test cards were presented first. The order of presentation was random, as determined by a random sequence generator.

4.2 Ethics

The study was approved by the Aston University Ethics Committee, the NHS South West 2 Research Ethics Committee, and the local ethics committee of the Gloucestershire Hospitals NHS Foundation Trust.

Following completion of the study, NRES were informed of the conclusion of the study. NRES acknowledged the study was formally closed as of the 16th June 2011. After this time, no further NHS patient data was collected.

4.3 Power Calculations

The sample size required was determined using the 'Power Analysis for ANOVA designs' program. The algorithm was accessed via the website: http://www.math.yorku.ca/SCS/Online/power/

	Single line spacing	Double Line Spacing	Triple Line Spacing
Single Word Spacing	X	X	X
Double Word Spacing	X	X	X
Triple Word Spacing	X	X	X

Table 2: Variations of typography spacing to be tested. *Nine variations of word and line spacing were used in the ERP test charts.*

The following parameters were set: (i) power size = 85%; (ii) error level = 0.05; (iii) effect size = 1.00.

With an effect size of 1.00, the relevant power analysis table for ANOVA designed trials (see Appendix 7) showed a power of 0.866, which relates to 86.6%. This corresponds to a sample size of N = 8, i.e. 8 participants are required for each level of the experiment. Therefore, a total of 24 participants were required.

4.4 Patient Selection

Inclusion criteria

To be included in the study, participants had to comply with the following criteria;

- Current outpatient of Gloucestershire Royal Hospitals NHS Foundation Trust
- Adult aged 18 years old and over
- Bilateral macular degeneration, either wet or dry type
- Any length of duration of macular degenerative changes
- Any age and either sex
- Distance acuity of no worse than 0.70 LogMAR in the better eye
- Distance acuity of no better than 0.30 LogMAR in the better eye
- First language of English with fluent reading abilities prior to vision loss

Exclusion Criteria

The following criteria excluded participants from the study;

- Ocular co-morbidity, i.e. glaucoma, significant cataract, diabetic retinopathy
- Amblyopia

4.5 Patient Details

The participant group was composed of 15 females and 9 males with an average age of 81.4 years ±6.9 years. All had age related macular degeneration in both eyes. Twenty participants were receiving Lucentis therapy to one eye and four participants were receiving Lucentis therapy to both eyes. The average visual acuity in the better eye was 0.44 logMAR, and in the worse eye it was 0.74 logMAR. The better eye had wet AMD in 67% of the participants and dry AMD in 33% of the participants. All participants completed all parts of the experiment.

Participant Number	1	2	3
Age (years)	84	79	89
Refraction R	-2.00/ +2.50 X 10	+2.00DS	+1.50 DS
Refraction L	-0.75/ +1.25 x 25	plano/ -1.00 x 100	+0.50 DS
R BCVA	1.36	0.58	0.34
L BCVA	0.54	0.78	0.64
Binoc BCVA	0.54	0.54	0.3
RE Diagnosis	Disciform scar	Wet AMD	Wet AMD
LE Diagnosis	Wet AMD	Wet AMD	Wet AMD

Participant Number	4	5	6
Age (years)	82	84	90
Refraction R	+4.50/+0.50 X170	-2.00/+0.25 X180	-1.25/ +3.00 X 25
Refraction L	+1.25/+0.50 X55	-0.25/ +0.75 X90	+1.00 DS
R BCVA	0.54	0.52	0.44
L BCVA	0.68	0.32	CF
Binoc BCVA	0.5	0.3	0.44
RE Diagnosis	Dry AMD	Wet AMD	Wet AMD
LE Diagnosis	Wet AMD	Wet AMD	Geographic atrophy

Participant Number	7	8	9
Age (years)	89	63	83
Refraction R	plano/+1.00 X 15	+0.25DS	plano/+0.75 X 20
Refraction L	-0.50/+2.25 X 10	plano/ +0.25 X 160	+0.50/+1.00 X 170
R BCVA	HM	0.96	1.64
L BCVA	0.38	0.34	0.48
Binoc BCVA	0.38	0.34	0.48
RE Diagnosis	Disciform scar	Wet AMD	Disciform scar
LE Diagnosis	Wet AMD	Dry AMD	Wet AMD

Participant Number	10	11	12
Age (years)	69	85	86
Refraction R	+ 3.25/+1.25 X 75	plano/+1.50 X 20	+1.25 +2.25 X 180
Refraction L	+4.00/ +1.00 X 70	-0.75/ +1.25 X 15	+1.50/+2.50 X180
R BCVA	0.54	0.54	1.34
L BCVA	0.68	0.56	0.74
Binoc BCVA	0.52	0.52	0.74
RE Diagnosis	Dry AMD	Wet AMD	Disciform scar
LE Diagnosis	Wet AMD	Dry AMD	Wet AMD

Table 3a: Patient details numbers 1 - 12. *BCVA= Best corrected visual acuity. Acuities are measured in logMAR units.*

Participant Number	13	14	15
Age (years)	87	76	80
Refraction R	-0.25/+3.50 X 175	+1.75DS	+2.25/+1.50X180
Refraction L	-0.25/ +2.50 X 170	+1.00/+1.00X140	+2.75/+0.50X145
R BCVA	0.34	0.42	0.3
L BCVA	0.62	0.96	1.36
Binoc BCVA	0.32	0.44	0.3
RE Diagnosis	Dry AMD	Wet AMD	Wet AMD
LE Diagnosis	Wet AMD	Wet AMD	Disciform scar

Participant Number	16	17	18
Age (years)	75	87	82
Refraction R	+2.50/+0.50X175	-0.25/ +1.75 X 175	+2.25DS
Refraction L	+1.50/+0.75X180	plano/+2.00 x170	+2.75DS
R BCVA	0.32	0.3	0.68
L BCVA	0.36	0.44	CF
Binoc BCVA	0.32	0.32	0.68
RE Diagnosis	Wet AMD	Wet AMD	Wet AMD
LE Diagnosis	Dry AMD	Wet AMD	Disciform scar

Participant Number	19	20	21
Age (years)	80	85	90
Refraction R	-1.00/+1.00 X 177	+2.50/+1.00x 175	-1.50 DS
Refraction L	-0.25/+1.00 X 25	+2.00DS	-1.75/ +0.75 X 45
R BCVA	0.46	0.70	1.36
L BCVA	0.72	CF	0.36
Binoc BCVA	0.42	0.72	0.36
RE Diagnosis	Wet AMD	Wet AMD	Disciform scar
LE Diagnosis	Wet AMD	Disciform scar	Wet AMD

Participant Number	22	23	24
Age (years)	83	72	74
Refraction R	+1.50/ +1.25 x 30	+0.25/ +0.75 x 70	+1.00/+2.25 x 170
Refraction L	+2.25DS	+0.50/ +1.50 x 125	+1.50/ + 2.75 x 10
R BCVA	0.32	0.7	0.43
L BCVA	0.64	0.42	1.36
Binoc BCVA	0.34	0.48	0.4
RE Diagnosis	Dry AMD	Wet AMD	Wet AMD
LE Diagnosis	Wet AMD	Dry AMD	Disciform scar

Table 3b: Patient details numbers 13 - 24. *BCVA= Best corrected visual acuity. Acuities are measured in logMAR units.*

5.0 Results: Critical Print Size

Critical print size for high and low contrast print was determined for each participant using the MNREAD charts.

Figures 18a-d depict the rate of reading curve for all participants. There was a trend for the high contrast print to be read faster than the reduced contrast print. Reading times for high and low contrast print were often equal when print size was above the critical print size. However, as print size decreased, the low contrast text reached the CPS more quickly and at relatively larger print sizes compared with high contrast print.

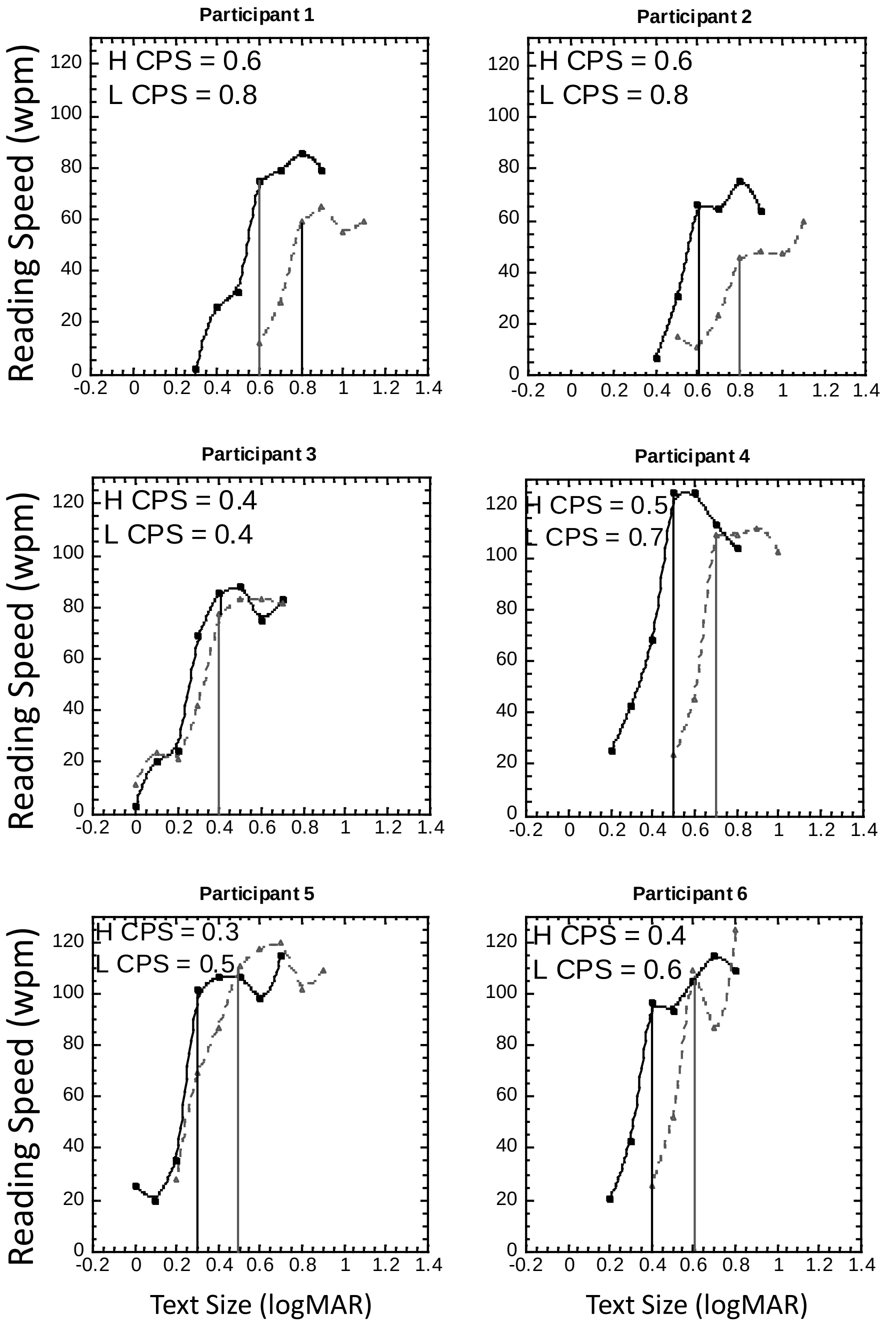


Figure 18a: Rate of reading curves for participants 1-6: *Filled black circles = full contrast reading time; grey triangles = reduced contrast reading times; vertical lines show CPS values; H CPS = high contrast critical print size; L CPS = low contrast critical print size.*

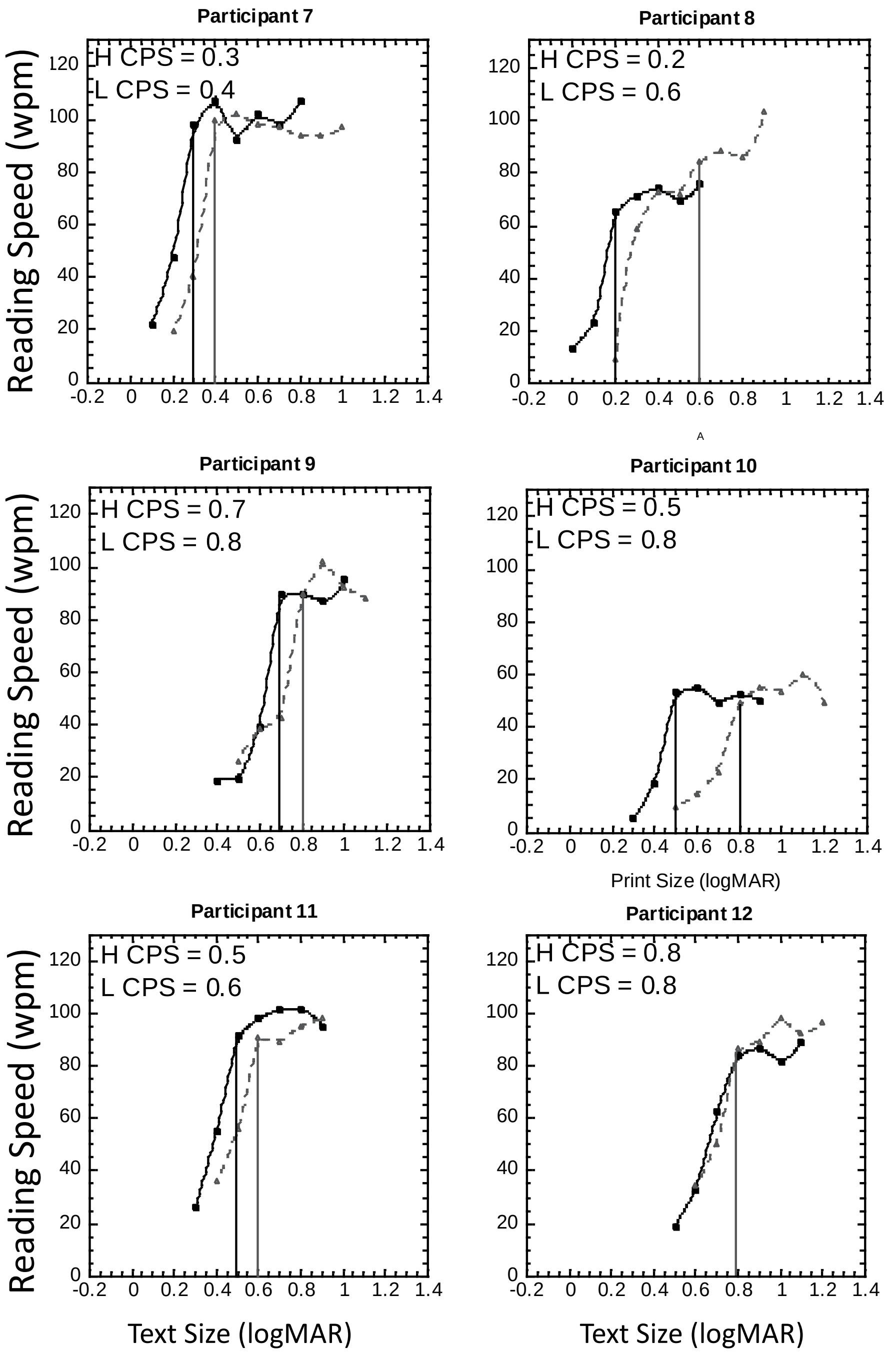


***Figure 18b: Rate of reading curves for participants 7-12**. Filled black circles = full contrast reading time; grey triangles = reduced contrast reading times; vertical lines show CPS values; H CPS = high contrast critical print size; L CPS = low contrast critical print size.*

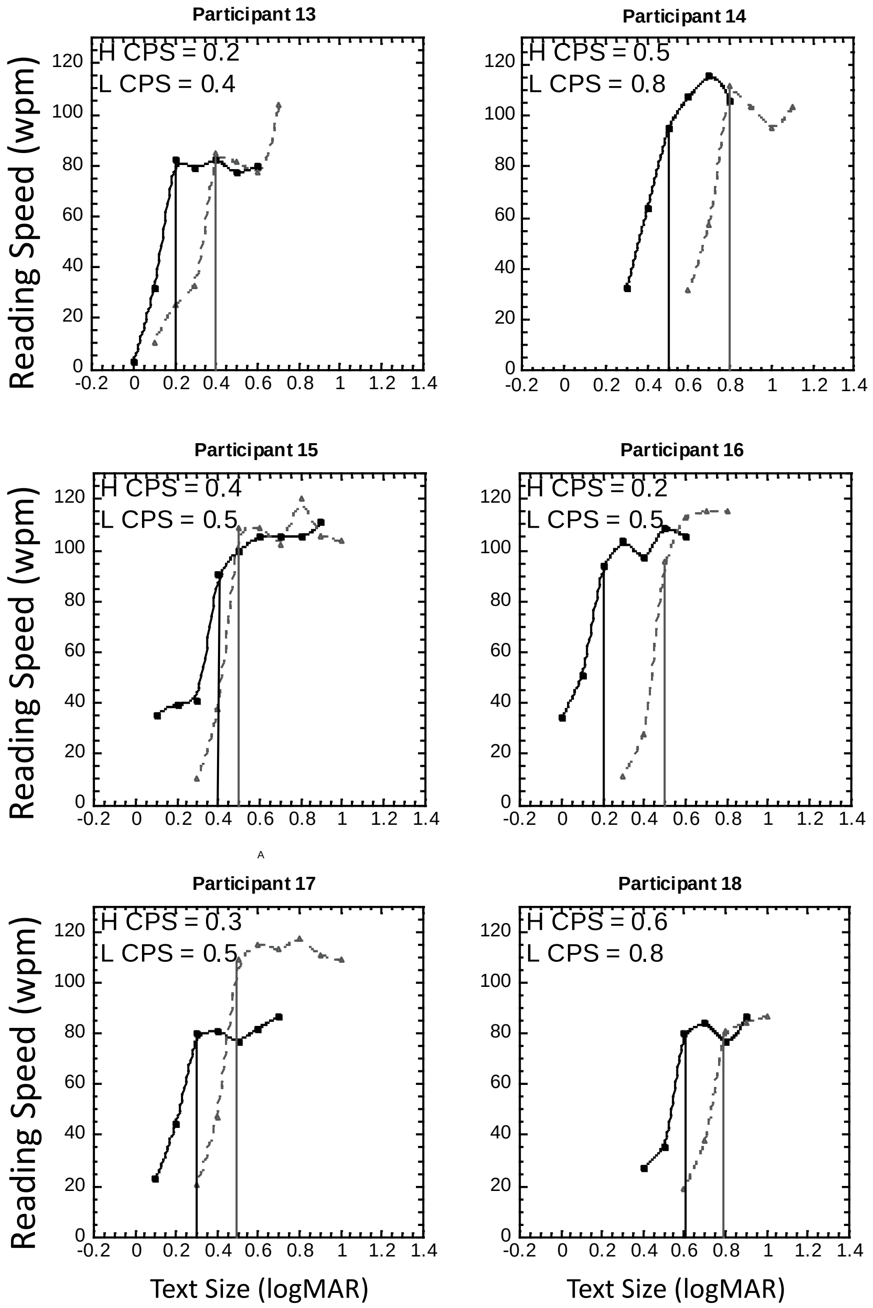


Figure 18c: Rate of reading curves for participants 13-18*.* *Filled black circles = full contrast reading time; grey triangles = reduced contrast reading times; vertical lines show CPS values; H CPS = high contrast critical print size; L CPS = low contrast critical print size.*

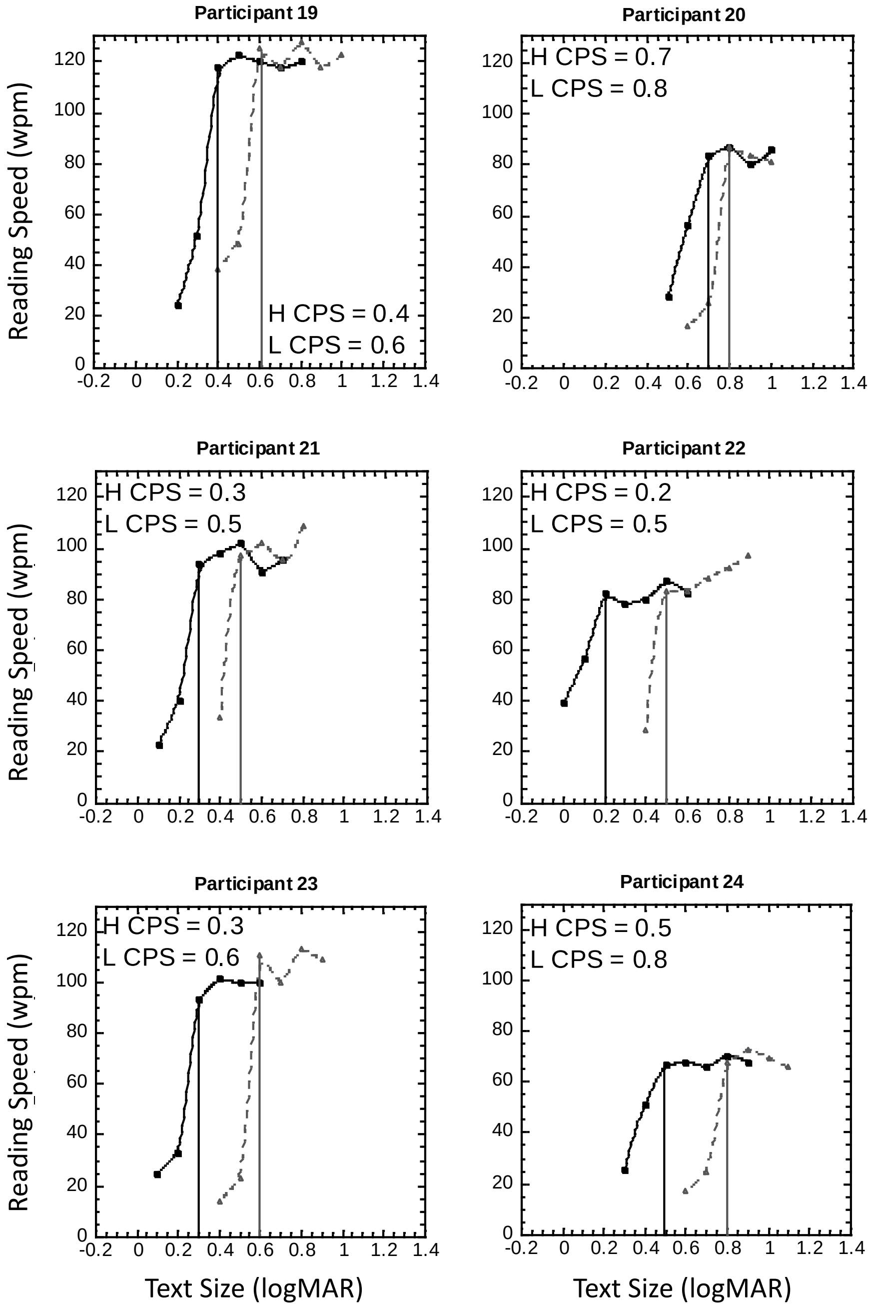


Figure 18d: Rate of reading curves for participants 19-24. *Filled black circles = full contrast reading time; grey triangles = reduced contrast reading times; vertical lines show CPS values; H CPS = high contrast critical print size; L CPS = low contrast critical print size.*

Figure 18a-d depicts mean CPS for high and low contrast MNREAD charts. The mean CPS for high contrast MNREAD chart was 0.425 logMAR, SD 0.175. The mean CPS for low contrast print was 0.63 logMAR, SD 0.146. The difference in means was 0.21 and this was found to be significant with a paired student t-test (t= -12.301, df =23, p <0.001). Therefore, critical print size is significantly reduced with low contrast text as opposed to high contrast text.

MNREAD data for each participant provided reading acuity for high and low contrast tests. For high contrast MNREAD data, CPS was on average 0.15logMAR (SD 0.06) larger than reading acuity, with the difference between CPS and reading acuity being significant with a paired student t-test (t= -11.679, df = 23, p <0.0001). For low contrast MNREAD data, CPS was 0.16 logMAR (SD 0.08) larger than reading acuity, with CPS and reading acuity being significantly different when testing with a paired student t-test (t= -9.467, df= 23, p< 0.0001).

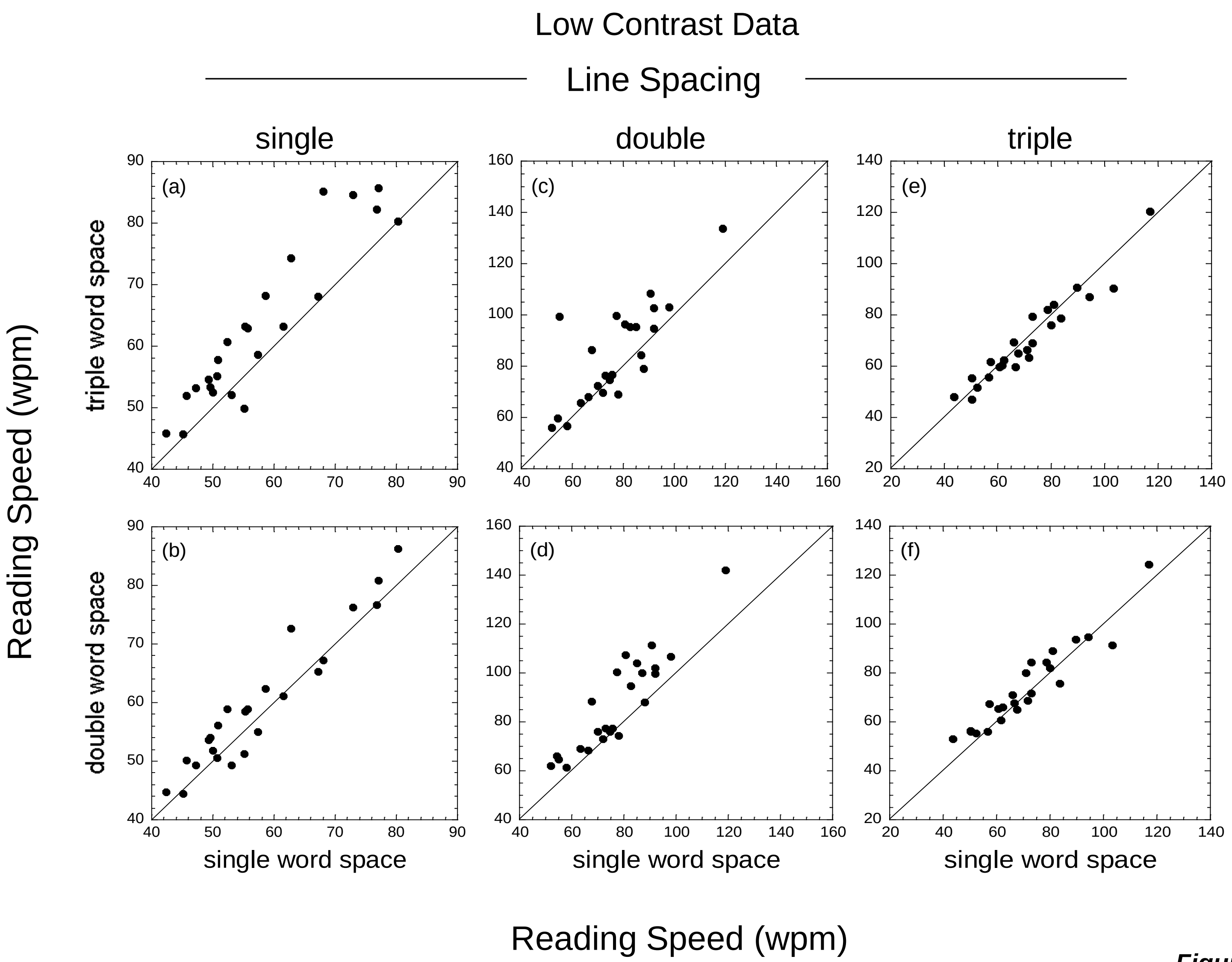
When combining high and low contrast data, CPS was 0.15logMAR (SD 0.07) larger than reading acuity. The difference between CPS and reading acuity for combined high and low contrast data was not significantly different (t= -0.692, df =23, p= 0.496).

6.0 Results: Effect of Text Spacing

6.1 Macular Disease Observers: Effect of Word Spacing.

Time taken to read the ERP cards that varied in word and/or line spacing was measured for all 24 observers with AMD, with reading speed computed as the number of correctly-read words per minute (wpm). Figure 19a shows, for low contrast ERP test cards, reading speeds for both single- versus double-word spacing (bottom panels) and single- versus triple-word spacing (top panels) for text passages with single, double or triple line spacing. The individual data points in each panel show the results for each participant, while the diagonal line in each panel is the 'line of no effect' (i.e. equal effectiveness of word spacing). In most conditions the data is clustered around the diagonal, indicating that word spacing had little effect on reading speed. For two conditions, however, a sign test indicated that enhanced word spacing yielded greater reading speeds [panels (a) and (d), $p < 0.01$]. In panel (a) reading speed of single line spaced text increased by 5.16 wpm when word spacing increased from single to triple (single character mean, 57.7 wpm, se 2.2; triple character mean, 62.8 wpm, se 2.6). In panel (d) reading speed of double line spaced text increased by 9.9 wpm when word spacing increased from single to double (single character mean, 77.2 wpm, se 3.2; double character mean, 87.1, wpm, se 4.1). Details of the statistical analyses for each condition are reported in the figure caption.

Figure 19b shows, for high contrast data, reading speeds for single- versus double word spacing (bottom panels) and single- versus triple word spacing (top panels) for ERP charts with single, double or triple line spacing. In all conditions, reading speed data are clustered around the line of no effect, indicating little effect of word spacing for the full contrast data [$p>0.01$ for panels a-f].



Low Contrast Data
Line Spacing
single
double
triple
(a)
(b)
(c)
(d)
(e)
(f)
triple word space
double word space
single word space
Reading Speed (wpm)

Figure 19a

Figure 19a. Effect of word spacing in macular disease: Low contrast data*. Reading speed (number of correctly-read words per minute) for both single- versus double-word spacing (bottom panels) and single- versus triple-word spacing (top panels) for text passages with single, double or triple line spacing. Results shown are for reading text with a letter contrast of 17.5%. The individual data points in each panel show the results for each participant; the diagonal line in each panel is the 'line of no effect'. With single line spacing, a sign test indicated that reading speed was significantly faster for triple word spacing than single word spacing (panel (a), $p < 0.01$). With double line spacing, reading speed was significantly faster for double than single word spacing (panel (d), $p < 0.01$). A sign test revealed no other significant effects (panel (b), $p = 0.31$; panel (c), $p = 0.02$; panel (e), $p = 0.31$; panel (f), $p = 0.31$).*

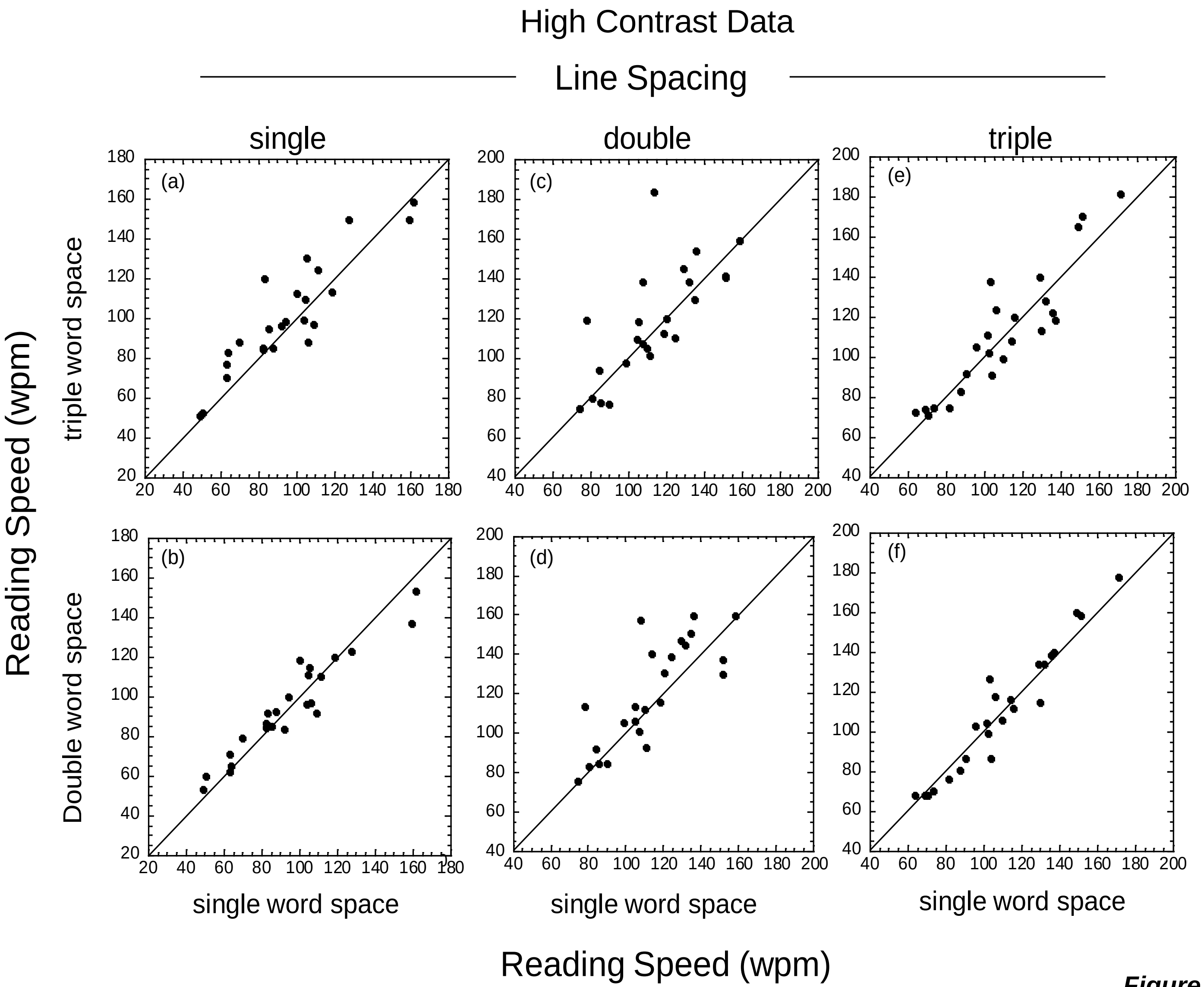

High Contrast Data
Line Spacing
single
double
triple
(a)
(b)
(c)
(d)
(e)
(f)
Reading Speed (wpm)
triple word space
Double word space
single word space
single word space
single word space
Reading Speed (wpm)

Figure 19b

Figure 19b. Effect of word spacing in macular disease: High contrast data*.* *Reading speed (number of correctly-read words per minute) for both single- versus double-word spacing (bottom panels) and single- versus triple-word spacing (top panels) for text passages with single, double or triple line spacing. Results shown are for ERP test charts with a letter contrast of 87.5%. The individual data points in each panel show the results for each participant; the diagonal line in each panel is the 'line of no effect'. A sign test revealed no significant effects (panel (a), p = 0.06; panel (b), p = 0.54; panel (c), p = 0.54; panel (d), p = 0.06; panel (e), p = 0.84; panel (f), p = 0.84).*

6.2 Macular Disease Observers: Effect of Line Spacing.

The reading speed data for macular disease observers was replotted in Figure 20a to accentuate the effect of line spacing. Figure 20a shows reading speeds for both single- versus double-line spacing (bottom panels) and single- versus triple-line spacing (top panels) for text passages with single, double or triple word spacing for low contrast ERP charts. Note that for each word spacing used, the data lie above or predominantly above the line of no effect, indicating that both double and triple line spacing yielded significantly greater reading speeds than single line spacing [$p < 0.01$ for conditions a – f].

In figure 20b, the data attained with high contrast ERP charts is shown. Reading speeds for single- versus double line spacing (bottom panels) and single- versus triple-line spacing (top panels) for ERP charts with single, double or triple word spacing are plotted. Note again that, for conditions a-d and f, the data lies above or predominately above the line of no effect, both double and triple line spacing yielded significantly greater reading speeds than single line spacing for these trials [$p < 0.01$for panels a-f]. Panel (e) shows data clustered around the diagonal, with a sign test showing no effect of line spacing for these conditions [$p = 0.152$].

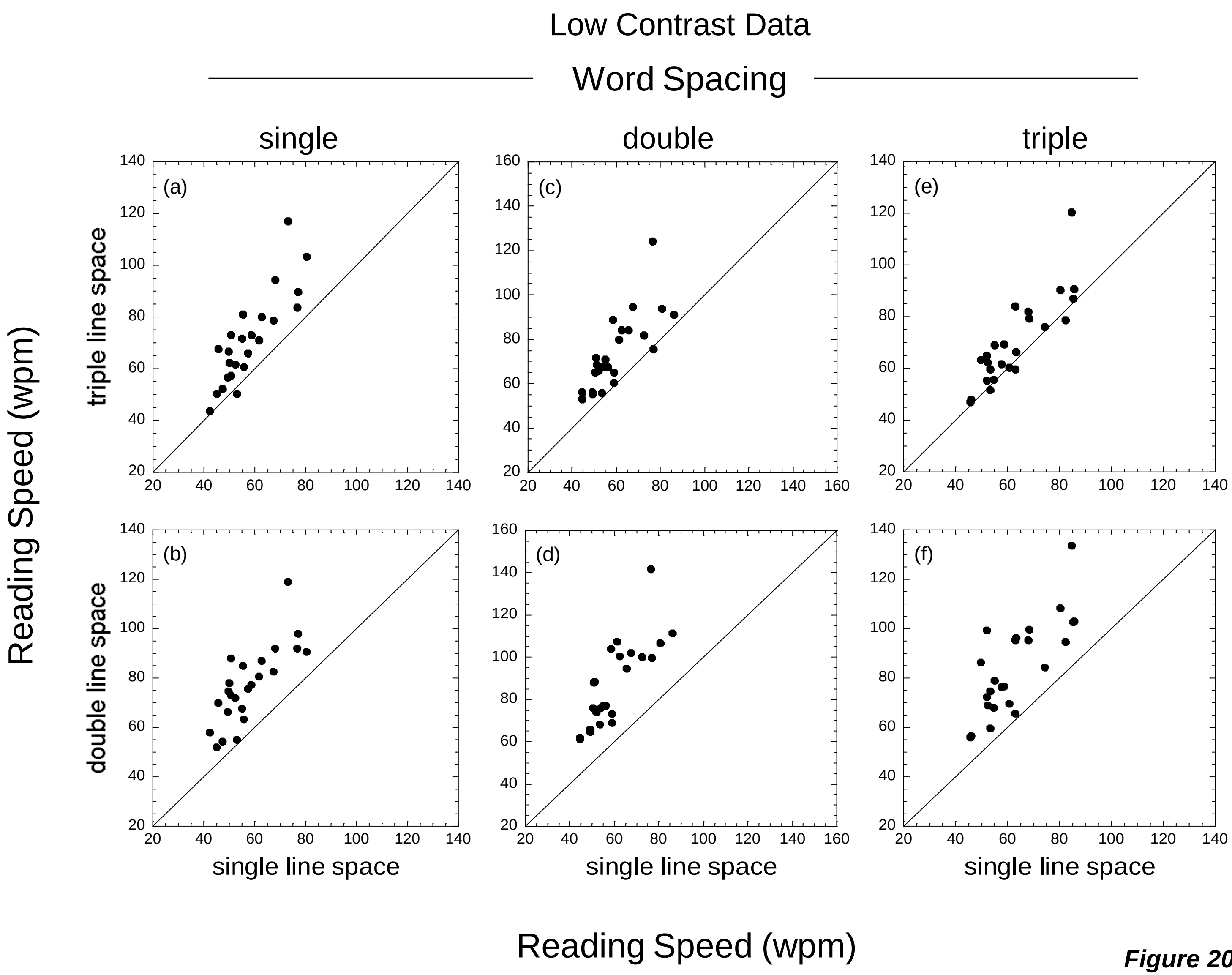
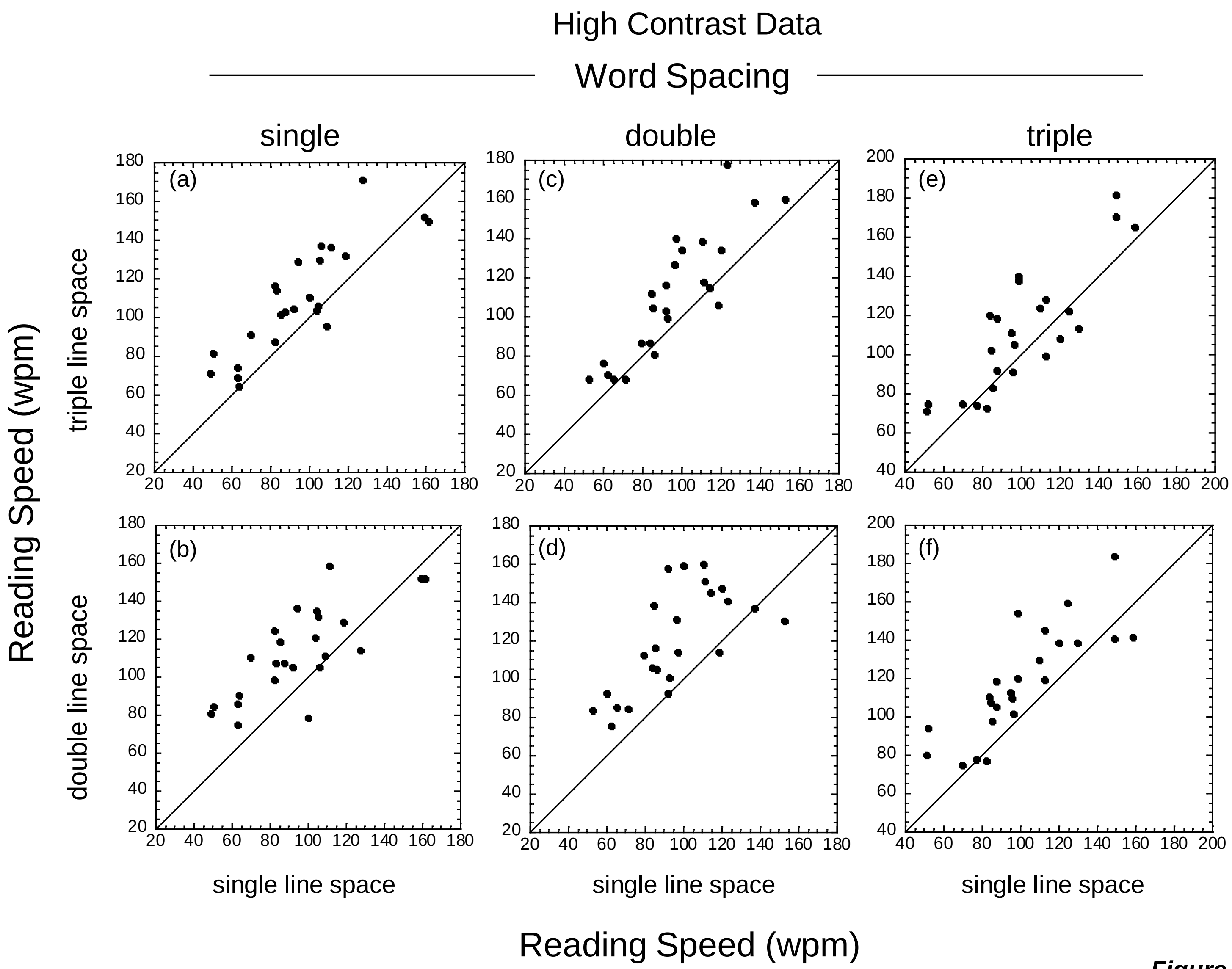

Low Contrast Data
Word Spacing
single
double
triple
(a)
(b)
(c)
(d)
(e)
(f)
triple line space
double line space
single line space
Reading Speed (wpm)

Figure 20a

F

Figure 20a: Effect of line spacing in macular disease: Low contrast data. *Reading speed for both single- versus double-line spacing (bottom panels) and single- versus triple-line spacing (top panels) for text passages with single, double or triple word spacing. Results shown are for text with a letter contrast of 17.5%. The individual data points in each panel show the results for each participant; the diagonal line in each panel is the 'line of no effect'. For each word spacing, a sign test indicates that both double and triple line spacing yield significantly greater reading speeds than single line spacing (p < 0.01 for conditions a – f).*



High Contrast Data
Word Spacing
single
double
triple
(a)
(b)
(c)
(d)
(e)
(f)
triple line space
double line space
single line space
single line space
single line space
Reading Speed (wpm)
Reading Speed (wpm)

Figure 20b

Figure 20b: Effect of line spacing in macular disease: High contrast data. *Reading speed for both single- versus double-line spacing (bottom panels) and single- versus triple-line spacing (top panels) for text passages with single, double or triple word spacing. Results shown are for ERP test charts with a letter contrast of 87.5%. The individual data points in each panel show the results for each participant; the diagonal line in each panel is the 'line of no effect'. With single and double word spacing, a sign test revealed reading speed was significantly faster for double and triple line spacing than single (panel a-d), p <0.01), and with triple word spacing, reading speed was significantly faster for double line spacing than single (panel (f), p<0.01). Reading speeds with triple line spacing and single line spacing was not significantly different for triple word spacing (panel (e), p = 0.152).*

6.3 Macular Disease Observers: Group-Mean Reading Speeds.

Figure 21 shows, for both low contrast text (a) and high contrast text (b), group mean (n = 24) reading speeds (wpm) for single, double and triple line spacing. For each line spacing used, results are shown for single (s), double (d) and triple (t) word spacing.

For reading speed measures completed with low contrast text (Figure 21a), a two-way repeated measures ANOVA revealed main effects of line space [$F(2,46) = 93.71$, $p < 0.001$, $\eta^2_p = 0.2601$] and word space on reading speed [$F(2,46) = 20.15$, $p < 0.001$, $\eta^2_p = 0.0176$]. A significant interaction between line space and word space was also observed [$F(4,92) = 9.33$, $p < 0.001$, $\eta^2_p = 0.0154$]. Note, however, that the generalized eta-squared measure of effect size (η^2_p) was 14.8 times greater for line space than word space.

A similar pattern of results was obtained for reading speed measures completed with high contrast text, though the effects were not as pronounced (Figure 21b). Nonetheless, a two-way repeated measures ANOVA revealed main effects of both line space [$F(2,46) = 22.35$, $p < 0.001$, $\eta^2_p = 0.0841$] and word space on reading speed [$F(2,46) = 3.98$, $p < 0.03$, $\eta^2_p = 0.0043$]. Note that the measure of effect size (η^2_p) was 19.6 times greater for line space than word space. Note also that, for measures obtained with high contrast text, the main effects were not qualified by an interaction between line and word space [$F(4,92) = 1.50$, $p = 0.21$, $\eta^2_p = 0.0029$].

Figure 22 shows the percentage increase in reading speed for each ERP card compared with the standard spacing of single line/ single word spacing. The combination of word and line spacing that provided the fastest reading speed was double line with double word spacing. For low contrast ERP cards (Figure 22a), double line with double word spacing was read 51% faster than the single line/single word spaced text. For high contrast ERP cards (Figure 22b) double line with double word spacing was read 26% faster than standard spacing.

Double line/double word spacing provides the largest percentage increase in reading speed for both low contrast ERP test cards and high contrast EPR test cards. Figure 23 illustrates the actual improvement to reading speed for each participant when text spacing is increased from single line/single word to double line/double word spacing. Each plotted point represents an individual participant's change in reading speed for both low and high contrast data (see figure 23). The plotted points are spread above and below the line of no effect, demonstrating participants who showed improvement with increased text spacing in low contrast were not the same participants who improved in high contrast conditions. A sign test confirms no significant relationship between improvements in reading speeds for high and low contrast ERP test cards, (p=0.31).

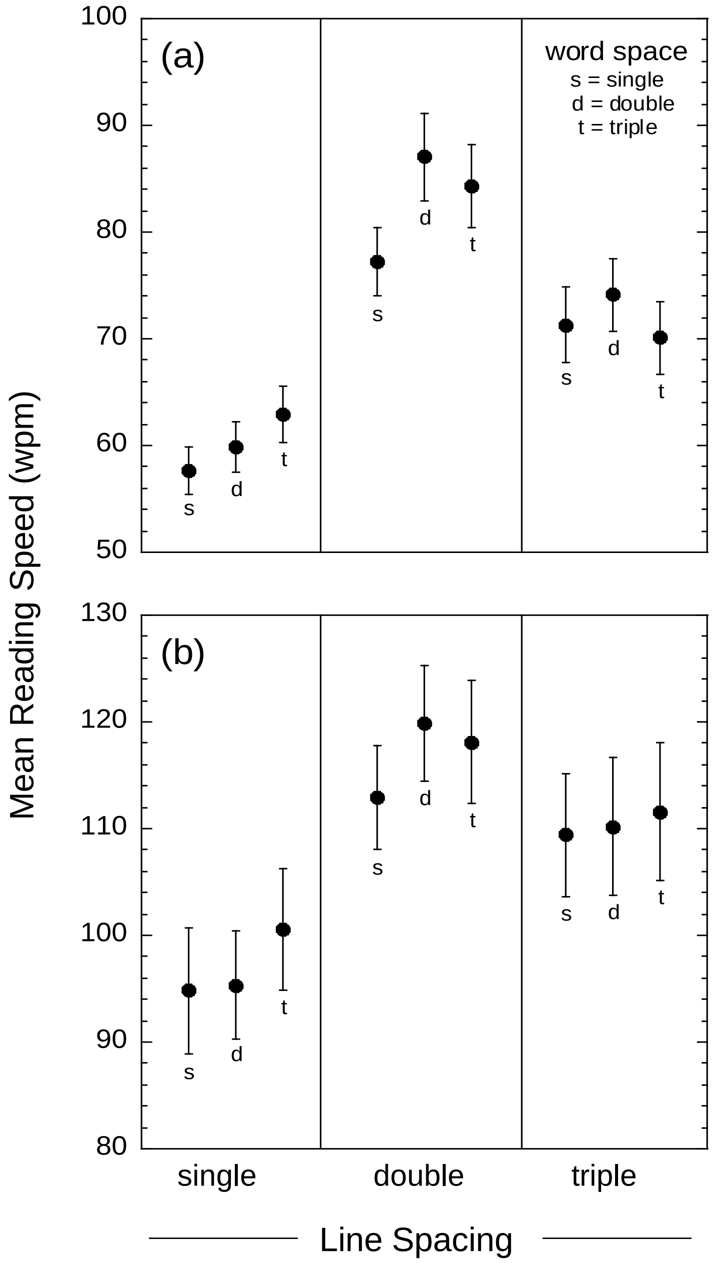


Figure 21. Summary graph depicting mean reading speeds for (a) low contrast text, and (b) high contrast text. *The greatest reading speed was measured using double word with double line spacing for both high and low contrast text, while the slowest reading speed was measured using single word with single line spacing. Overall, reading speeds were faster using high contrast text compared to low contrast. Error bars represent +/- one standard error.*

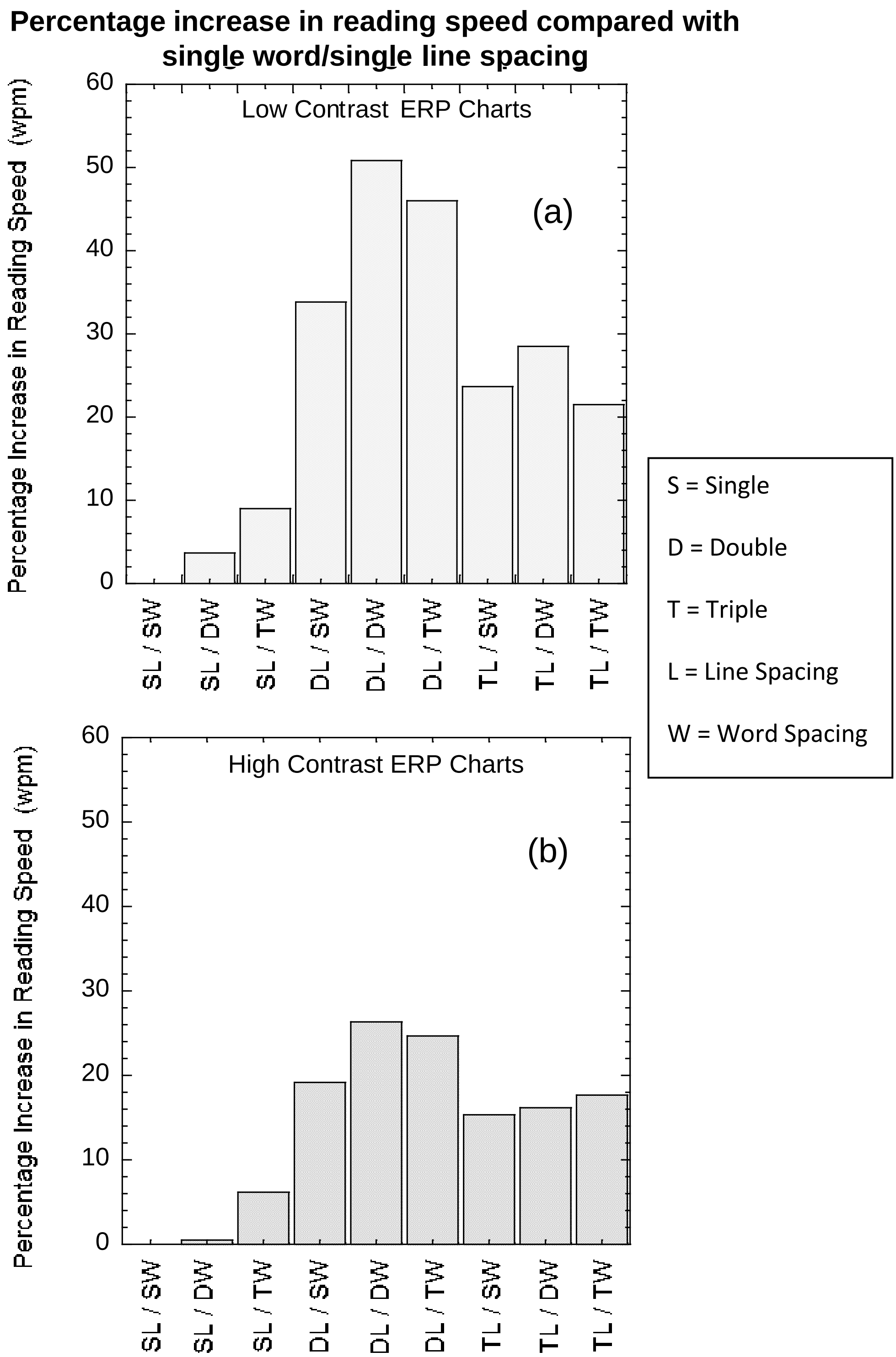

Percentage increase in reading speed compared with single word/single line spacing
Low Contrast ERP Charts
(a)
High Contrast ERP Charts
(b)
Percentage Increase in Reading Speed (wpm)
0
10
20
30
40
50
60
SL / SW
SL / DW
SL / TW
DL / SW
DL / DW
DL / TW
TL / SW
TL / DW
TL / TW
S = Single
D = Double
T = Triple
L = Line Spacing
W = Word Spacing

Figure 22

Figure 22: Bar chart to show percentage increase in reading speed for all combinations of word and line spacing compared to single word/ single line spacing for (a) low contrast text, and (b) high contrast text.

Single word/single line spacing provided the slowest reading speed for both high and low contrast data. The bar chart shows the percentage increase in reading speed for high and low contrast as compared to single word/single line spacing.

Double line/double word spacing provided an increase in reading speed of 51% for low contrast ERP cards (Figure 21a) and a 26 % increase for high contrast ERP cards (Figure 21b).

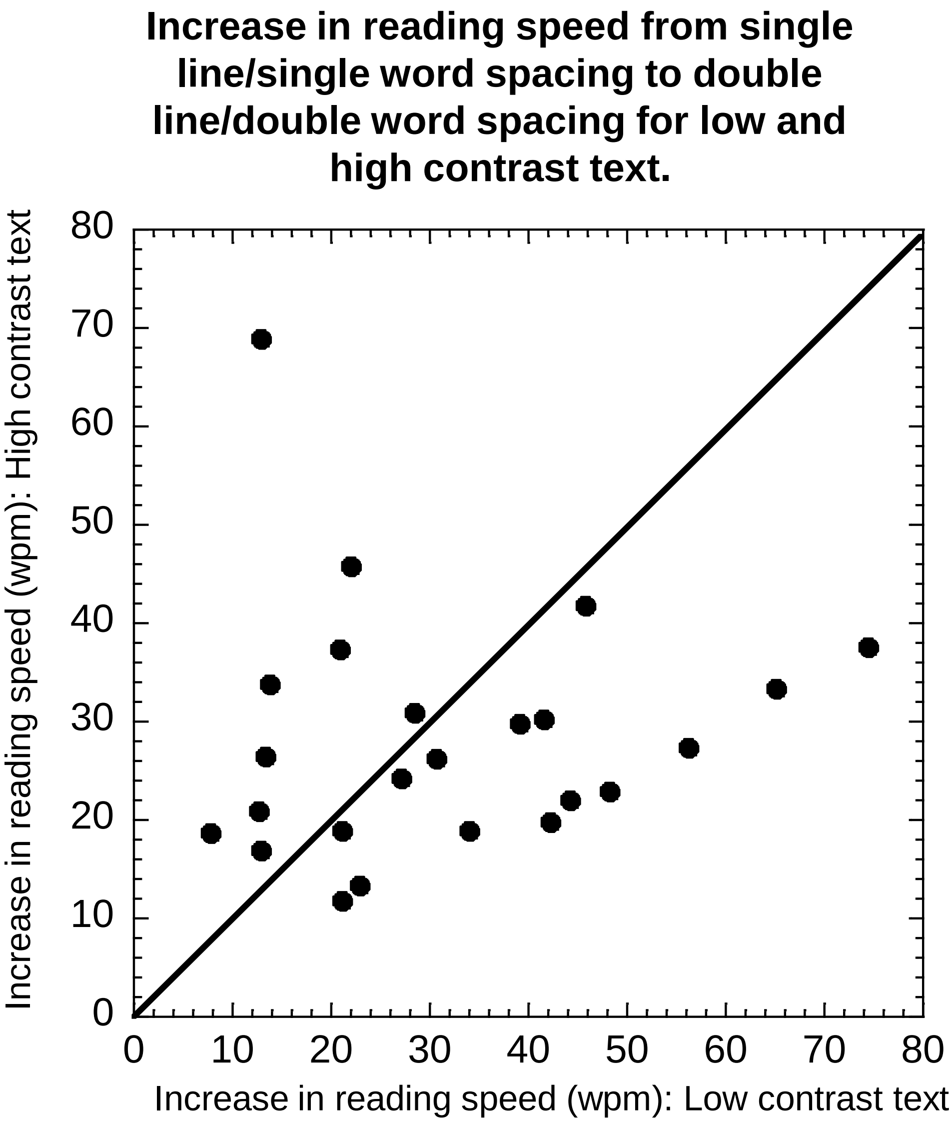


Figure 23: Increase in reading speed for low and high contrast data. *The greatest improvement to reading speed occurred when text spacing increased from single line/single word to double line/double word for both high and low ERP test cards. The improvement to reading speed for each participant for high and low contrast data is plotted in the graph. Participants who showed the greatest improvement with increased text spacing in low contrast were not the same participants who improved in high contrast conditions. A sign test confirms no significant relationship between improvements in reading speeds for high and low contrast ERP test cards, (p=0.31).*

6.4 Macular Disease Observers: Group-Mean Number of Error

For each condition employed, a small number of words were read incorrectly or omitted. These errors were recorded and are shown as group-mean values in Figure 24 for both low (a) and high contrast text (b). For each line spacing, results are shown for single (s), double (d) and triple (t) word spacing. Averaged across different word spacings, the number of errors recorded when reading low contrast text was 2.6 (se, 0.2), 0.9 (se,0.2) and 1.3 (se, 0.2) for single, double and triple line space, respectively (Figure 24a). For high contrast text, the number of errors was 1.4 (se, 0.2), 0.8 (se, 0.1) and 0.6 (se,0.1) for single, double and triple line space, respectively (Figure 24b). Averaged across all conditions, the mean number of errors made when reading low contrast text was 1.6 (se, 0.1), while the mean number obtained with high contrast text was 0.9 (se, 0.1). Note that the general findings reported above for reading speed (Figures 21 and 22) are reflected in the mean number of errors made: slower reading speeds were generally associated with a higher number of reading errors.

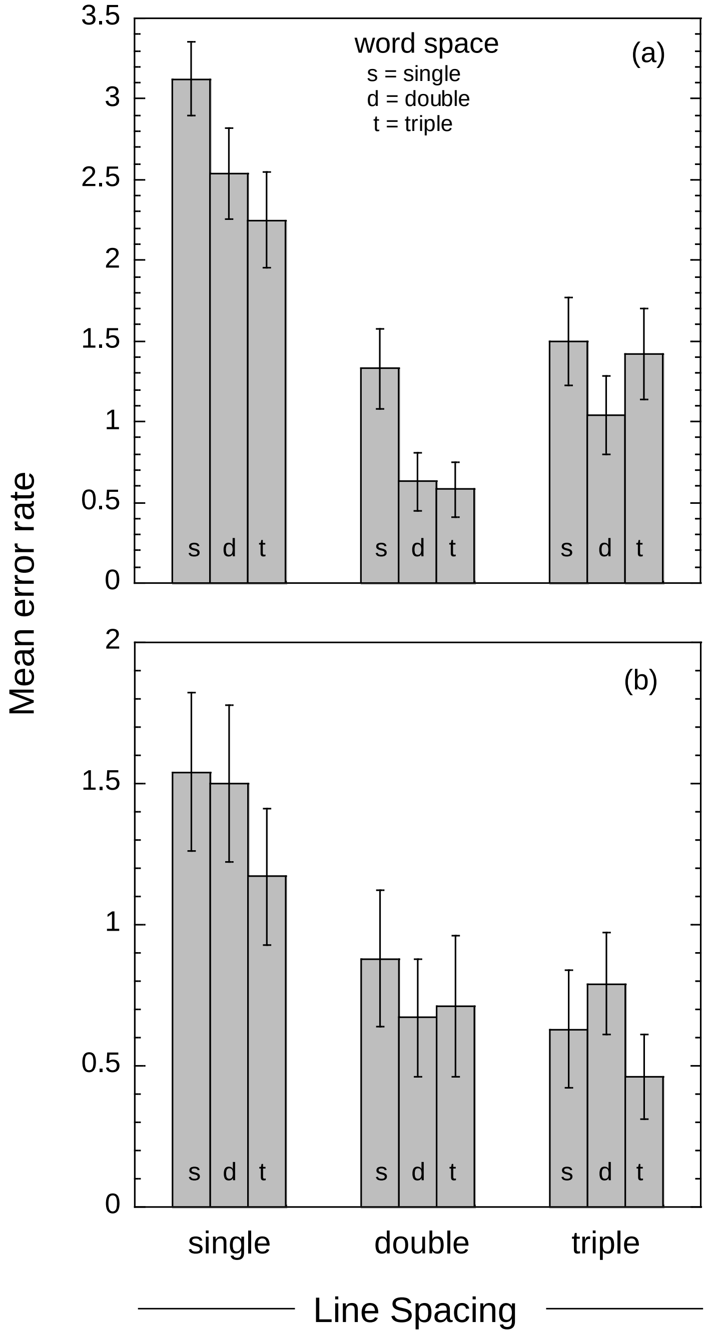


Figure 24: Summary graph depicting the mean number of errors made when reading the ERP charts for (a) low contrast text, and (b) high contrast text. *More errors were made when reading single line spaced text for both high and low contrast text. Low contrast text of single line spacing had the greatest number of errors for all variations of word spacing.*

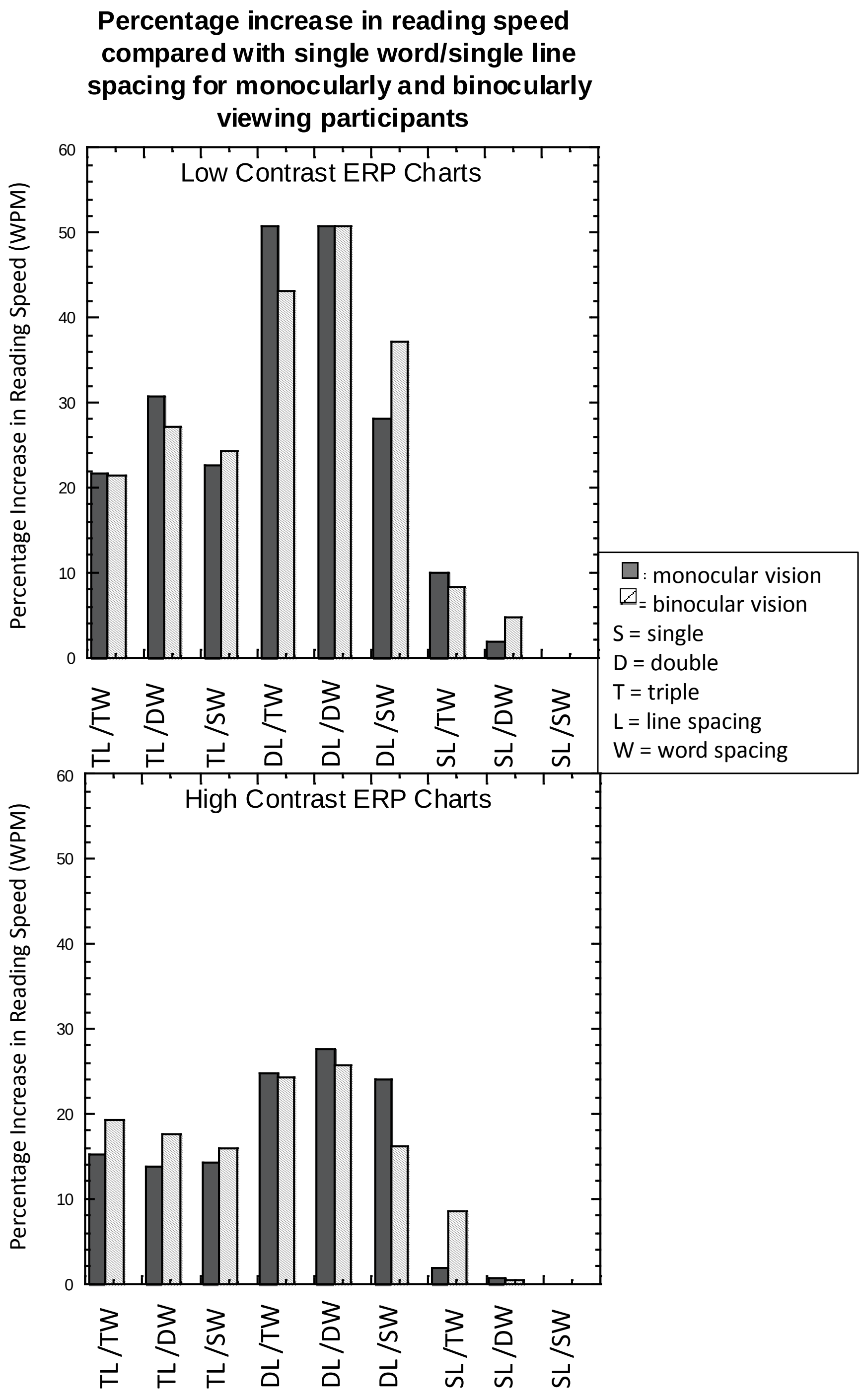


Figure 25: Bar chart to show percentage increase in reading speed compared to single line/single word spacing for participants using monocular vision and binocular vision. *Slowest reading speeds were measured using single line/single word spacing for both monocular and binocular participants when using high and low contrast ERP test cards.*

Percentage increases in reading speeds were not significantly different when comparing monocularly viewing participants and binocularly viewing participants (see text for statistical alnalysis).

6.5 The Effect of Text Spacing on Reading Speed for Monocular and Binocular Participants

All participants used binocular vision during measurement of reading speeds. However, when considering the best corrected visual acuity (BCVA) of the 24 AMD patients (see table 3a and 3b), 10 patients had less than 1.30 logMAR (6/96 snellen equivalent) in their fellow eye. These 10 patients could be considered to be using monocular vision when reading because the vision in the fellow eye is poor. The percentage increase in reading speed as measured with the ERP test cards compared to single line/ single word spacing for both monocular and binocular patients is shown in figure 25. For both monocular and binocular participants, the increase in reading speed was more distinct for low contrast ERP test cards compared to high contrast ERP test cards (see figure 25).

For high contrast ERP test card data, the increase in reading speed for monocular and binocular patients was not significantly different when tested using a paired student t-test ($t = -0.449$, $df = 8$, $p = 0.665$). The same is true for low contrast ERP test card data, with monocular and binocular patients not showing significantly different increases in reading speed with a paired student t-test ($t = -0.0415$, $df = 8$, $p = 0.978$). Therefore, the effect of text spacing on reading speed is unaffected by monocular or binocular vision.

General Discussion

7.0 General Discussion

This study assessed the ability of both normally-sighted individuals and macular disease patients to read using their peripheral vision. For both subject groups, the reading tests employed were designed to model as closely as possible the natural reading process – all measures allowed for free binocular saccadic eye movements, and all subjects were required to read (and comprehend) whole sentences. Such an approach is rarely adopted in reading research, with many previous studies employing rapid serial visual presentation and/or single word recognition tasks.

The principal aim was to assess the effects of text crowding on reading performance and the results of the experiments are unequivocal: crowding is detrimental to reading with peripheral vision in both normally-sighted individuals and AMD patients, and its effects can be minimized with a modest increase in text spacing, especially line spacing. The findings provide evidence to suggest that enhanced text spacing may provide a simple and effective means of improving reading performance in many individuals with central vision loss.

Preliminary measures (see Section 2.0) on normally-sighted individuals were used to define an appropriate textual search space for the main clinical trials on AMD patients. The initial measures also showed that double line spacing significantly improved reading performance, with reading speeds for double line spacing approaching that of unflanked text. Finally, a doubling of word space enhanced reading performance for both observers (SJA, SB-W), though the measures only reached significance for SB-W. Therefore, the benefits of increased word spacing were not as clear-cut as those for increased line spacing. Given these initial results, and to ensure the effects of increased text spacing were comprehensively investigated, the search space for the main clinical trials on AMD patients was extended to include all permutations of single, double and triple line and word spacing.

Clinical measures on AMD patients assessed reading ability using both full (87.5%) and reduced (17.5%) contrast text. Low contrast text was used to enhance test sensitivity and avoid potential ceiling effects, and also to mimic a possible reduction in letter contrast with light scatter from media opacities. CPS was calculated for both high and low contrast MNREAD charts for each observer. Note that when averaged across all observers, low contrast charts measured CPS to be 0.20 logMAR larger than high contrast charts (mean CPS low contrast, 0.63 logMAR, SD, 0.15; and mean CPS high contrast, 0.43 logMAR, SD 0.18). Therefore, it is clear that normal reading material for AMD patients should be presented with as high a contrast as possible.

Results from the modified MNREAD tests allowed comparison between reading acuity (the smallest text size just discernible) and CPS for both high and low contrast MNREAD data. When averaged across all data, CPS measured 0.15 logMAR (SD 0.07) larger than reading acuity. Thus, when reading material is designed for an observer of known reading acuity, text should be at least 0.15 logMAR larger to ensure reading ability is not limited by text size.

The main clinical trials measured the effects of line and word spacing on the reading ability of AMD patients. The results provide evidence that enhanced text spacing significantly increases reading speed and reduces the number of reading errors made. The fastest reading speeds measured, which also had the fewest number of errors, were for passages with double line and double word spacing. The particular importance of enhanced line spacing for macular disease sufferers is best seen in the scatter plots of Figures 20a and 20b. Given a passage of text to read, for single, double and triple word spacing, the reading speed of every single individual assessed (n = 24) was faster with double line spacing than single line spacing (bottom panels of Figure 20a). A similar affect can be seen in Figure 20b (panels b, d and f), where high contrast text data shows increased reading speeds for double line spacing compared with single spacing for most participants.

With standard text defined as single line with single word spacing, the beneficial effect on reading speed of increased text spacing is clearly evident in Figure 22. Figure 22a shows that, in comparison with standard spaced text, low contrast ERP cards yielded reading speeds 51% faster with double line and word spacing. This corresponds to an increase from 57.7 wpm (SD 2.2) using standard spacing to 87.1 wpm (SD 4.1) using double spacing. The effect is also seen in Figure 22b for high contrast data, in which reading speed increased from 94.8 wpm (SD 5.9) using standard-spaced high contrast text to 119.8 wpm (SD 5.5) using double-spaced text. This equates to an increase in reading speed of 26%. Previous studies into coefficients of repeatability for visually impaired readers recommend a change of at least 25% in reading speed to signify a clinically significant difference (Submaranian et al., 2009). Using this criterion, the current study confirms that, compared with standard-spaced text, the combination of double line and word spacing provides a clinically significant increase in reading speed for both high and low contrast text. The increase in reading speed of 26% for high contrast text only just exceeds Submaranian's definition of significance, while the increase in reading speed for low contrast text far surpasses it. This demonstrates that by using both high and low contrast MNREAD and ERP test cards in these experimental trials, a potential ceiling effect was avoided. Using full contrast stimuli alone would not have provided such definitive results.

The increase in reading speed between single and double line spacing suggests the effect of crowding reduces as vertical text space increases. Critical spacing is achieved and maximum reading speed is attained when double line and word spacing is used. As text spacing increases further, critical spacing is surpassed and reading speed begins to decrease. Note that triple line spacing provided reading speeds slower than double line spacing, but faster than single line spacing (Fig. 21). As noted by Ehsaei et al (2013), visual acuity reduces with increased retinal eccentricity at a faster rate in the vertical than the horizontal retinal meridians. This corresponds to larger receptive fields with increasing eccentricity along the vertical retinal meridian compared to horizontal. Larger receptive fields require greater critical spacing to avoid crowding. This may account for greater effect of increased vertical spacing, i,e line spacing, compared with horizontal spacing, i.e word spacing, as demonstrated in the results of this study.

A doubling or tripling of word space was helpful in some macular disease sufferers, but not all (see Figure 19a). A repeated-measures ANOVA revealed main effects of both line and word spacing for both high and low contrast data. However, it is important to note that the generalized eta-squared measure of effect size (η^2_p) was 15 times greater for line space than word space for low contrast text, and 20 times greater for high contrast text. Line spacing clearly has a greater effect on reading speed than horizontal inter-word spacing. Analysis of the raw data showed that participants who showed the greatest improvement with increased line spacing were not the same participants who benefited the most from increased word spacing. Note that patient fixation strategy was not known and therefore some of the differences in the crowding effect between subjects may be attributable to differences in fixation strategy.

When examining raw data from each participant collected from ERP test cards trials, there are occasional examples of participants reading low contrast text faster than high contrast text for an equivalent variant of word and line spacing. This contradicts the expectation that high contrast text should be a simpler task, and therefore reading speed should be greater for high contrast text compared with low contrast text. Such variations may be explained by, ‘experiment noise’, for example, loss of concentration or mistakes made by the observer. It may also be the result of variations in contrast sensitivities due to media opacity. Any participants with significant cataracts were excluded from this experimental trial, however it may have been more prudent to only include pseudophakic observers with clear intraocular lenses. This may have standardised contrast sensitivities and improved the quality of collected data.

When considering data from AMD patients, the rate of errors was highest for single line spacing for both full and reduced contrast text. The least number of reading errors (i.e. misread or omitted words) were made when reading text with double line and double word spacing (Figure 24). As reading errors interrupts fluent reading and reduces comprehension, a textural arrangement that reduces the number of errors will therefore improve reading performance and, presumably, increase enjoyment of the task.

The increase in reading speeds with enhanced word spacing measured in this study is in general agreement with previous reports (Rayner et al., 2010, Slattery and Rayner, 2013, Dreighe et al, 2005, Paterson and Jordan, 2010). Slattery and Rayner (2013) have recently argued that reduced inter-word spacing causes disruption to word identification processes and this accounts for the beneficial effect of increased word spacing (Rayner et al 2010, Slattery and Rayner, 2013). Drieghe et al (2005) attribute the increase in reading speed to reduced duration of fixation and faster word recognition when reading with double word spacing compared with single word spacing.

However, reports on the effect of line spacing on eccentric reading ability provide conflicting evidence. Chung (2004) and Calabrese, (2010) describe a beneficial effect of increased line spacing, which is in agreement with the findings of this study. However, studies by Bernard et al., (2007) and Chung (2008) report no significant effect of line spacing, which runs contrary to the results presented here. Several methodological differences may account for this difference: (i) the use small sample sizes [N = 4 for Chung (2008) and N = 7 for Bernard et al.], (ii) the use simulated scotomas, and (iii) the use of RSVP viewing techniques. Presumably the results of Calabrese (2010) offer more reliability because of the larger sample size used in that study (N = 90 eyes). Table 4 shows a summary of the results from

Calebrese et al., Chung (2008) and the main clinical results reported in this thesis. Note that, despite the small sample size employed, Chung did find a consistent improvement for double *versus* single line spacing – the mean increase in reading speed reported by Chung (45%), is similar to the increase reported here for low contrast data (34%).

The methodology used by Calabrese et al. (2010) is comparable to that in the current study in that observers with genuine AMD read complete sentences presented with black letters on a white background. Figure 26 shows replotted data from the Calabrese et al. (2010) study in which individual observers are represented by small open circles, plotted to show the improvement produced when line spacing increased from single to double. Note that the improvement ranged from less than 10% to greater than 40%. Results from the four main conditions tested in the ERP trials are replotted for comparison, using blue and red circles (see Figure 26). The ERP high contrast card with single word spacing is the most similar test condition to Calabrese et al. (2010). Improvement in reading speed for this condition was 19% in the current study, which is similar to the 17% improvement reported by Calabrese et al. (2010).

Data source	Measure	Speed, wpm 1-line space	Speed, wpm 2-line space	Improvement wpm	Improvement %
Calabrese et al 2010 *(N=90 eyes, 61 Ss)*	Mean	43.02	50.17	7.14	16.60
Chung et al 2008, RSVP *(N=4 Ss)*	Mean	43.10	62.59	19.49	45.22
WS=1, high contrast *(N=24 Ss, our data)*	Mean	94.80	112.88	18.08	19.07
WS=2, high contrast	Mean	95.34	119.84	24.50	25.70
WS=1, low contrast	Mean	57.71	77.20	19.48	33.76
WS=2, low contrast	Mean	59.82	87.07	27.25	45.56

***Table 4: Comparison of reading studies in AMD**. Summary of improved reading speeds with double line-spacing in three studies of AMD patients. WS = word spacing. Ss = subjects. Improvement in wpm, for a given observer, is reading speed with double line spacing minus reading speed with single line spacing. The column 'Improvement, wpm' shows the mean improvement.*

Figure 26 reinforces the conclusion that double word spacing (red symbols) enhances the effect of double line spacing, such that the improvement in mean reading speed for AMD observers in the current study increased to 26% with high contrast text and 46% with low contrast text (see Table 4). Double line with double word spacing was particularly helpful to AMD observers when the text contrast was low – the combined benefit of double line with double word spacing over single line with single word spacing was 51% (see Figure 22). Because AMD observers with media opacities are likely to have reduced contrast sensitivity, they stand to benefit from a doubling of both word and line spacing even more so than observers with clear media.

The distinct advantage of double line spacing, and to a lesser extent double word spacing, in improving reading ability for peripherally viewed text can be explained by the reduction in deleterious effects of visual crowding: increasing line spacing allows flanking sentences to stimulate adjacent integration fields. In addition, the visual span is smaller when using peripheral vision, and therefore more intra-word saccades will be required to read a sentence (Pelli et al., 2007). If enhanced line spacing minimises the duration of fixation (Dreighe, 2005), reading speed will increase despite the need for more intra-word saccades. Unfortunately, this study does not have direct evidence in support of this statement as eye movements in the macular disease group could not be recorded. However, anecdotal observations suggest that, with single line spacing, AMD sufferers often begin to re-read the same line as they were unable to ascertain which line was the next line down. A line of text in relative isolation will presumably provide a more powerful cue for directing eye movements (Findlay, 1997, Sunness and Applegate, 2005).

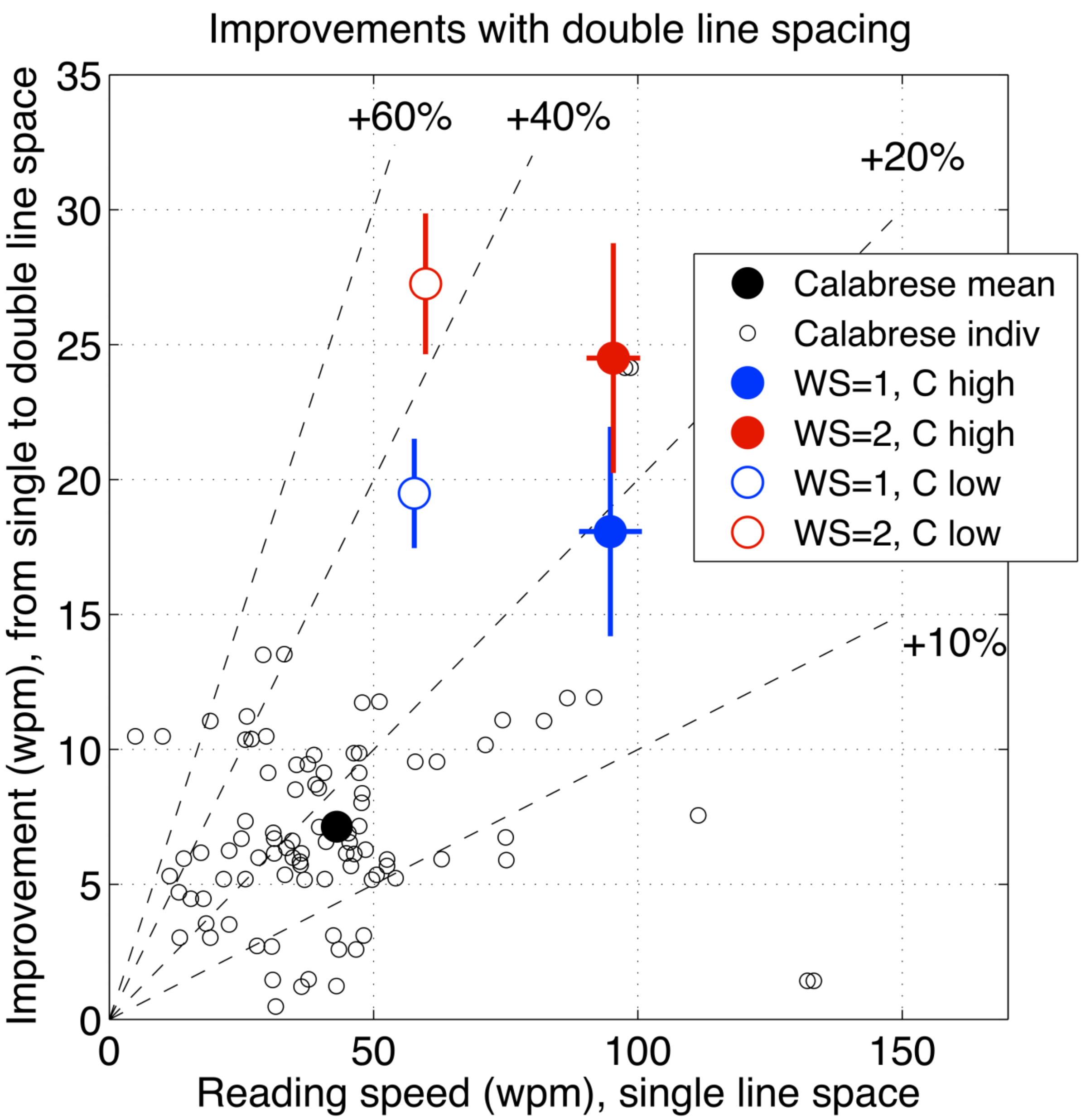

Improvements with double line spacing
Improvement (wpm), from single to double line space
Reading speed (wpm), single line space
0
5
10
15
20
25
30
35
0
50
100
150
+60%
+40%
+20%
+10%
Calabrese mean
Calabrese indiv
WS=1, C high
WS=2, C high
WS=1, C low
WS=2, C low

Figure 26

Figure 26: Comparison of reading studies in AMD. *Improvements in mean reading speed of AMD patients produced by double line spacing, from the present study and Calabrese et al. (2010). Improvement is defined as reading speed with double line spacing minus reading speed with single line spacing, in wpm. Abscissa plots baseline reading speed with single line spacing. Dashed line represent 10%, 20%, 40% and 60% improvement, as marked. Large circles are mean reading speeds (wpm): black circle, Calabrese et al. (2010); red and blue circles, means ±1 se from the present study, with single or double word spacing (WS), and low or high contrast (C). Small circles: individual observers from Calabrese et al (2010)*

A promising area of scientific research is the development of training algorithms for subjects with central vision loss. Training sessions employing repetitive recognition tasks and peripheral vision have proved to increase reading speeds by between 41% and 83% (He et al. 2013, Chung et al. 2004, Yu et al. 2010, Lee et al. 2010). The increase in reading speeds following perceptual training are comparable to the increase in reading speeds illustrated in Figure 22. The 51% faster reading speeds measured using double word and line spacing compared with standard spacing (see Figure 22) shows a simple and effective way to enhance reading ability without the subject enrolling in a training programme. However, the combination of perceptual training and optimal text spacing may prove to be even more effective in improving reading performance in patients with central visual field loss, and should be given high priority as a direction for future reading research.

The AMD participants assessed in this study had been treated with anti-VEGF inhibitors in at least one eye. Visual acuities were relatively good, ranging from 0.3 logMAR to 0.7 logMAR. While this residual acuity range is increasingly common for patients with AMD, future studies should investigate whether the findings of this study hold true for patients with vision less than this acuity range.

Microperimetry assessment was not performed in this research study. Future research into the effects of typography on reading with macular disease would benefit from measurement of scotoma size, PRL location and gaze stability. These factors have been recognized as good predictors of mean reading speed in the presence of a macular scotoma (Ergun et al. 2003, Calabrese et al. 2011, Crossland et al, 2004, Greenstein et al 2008) and therefore should be included in mixed-effects analysis when considering the effects of typography spacing on reading speed.

As stated above, the advent of new treatment for AMD coupled with an aging population has led to a large group of AMD sufferers with an acuity of 0.3 – 0.7 logMAR. A principle frustration of this group is the inability to read efficiently (Mitchell et al 2002). The results of this study suggest that enhanced text spacing reduces the detrimental effects of peripheral visual crowding, yielding a significant increase in reading speed and a reduction in the number of reading errors. It is concluded that, whenever possible, optometrists should recommend to individuals with macular disease that they use double line spacing and double-character word spacing to maximize their reading efficiency. Today, such changes are easily implemented with many modern handheld reading tablets. Reading tablets also have the advantage of being able to display text at or near maximum contrast, and to do so with a multitude of font sizes. These simple modifications to text layout are an uncomplicated, cost-effective and efficient method to improve reading ability for AMD patients.

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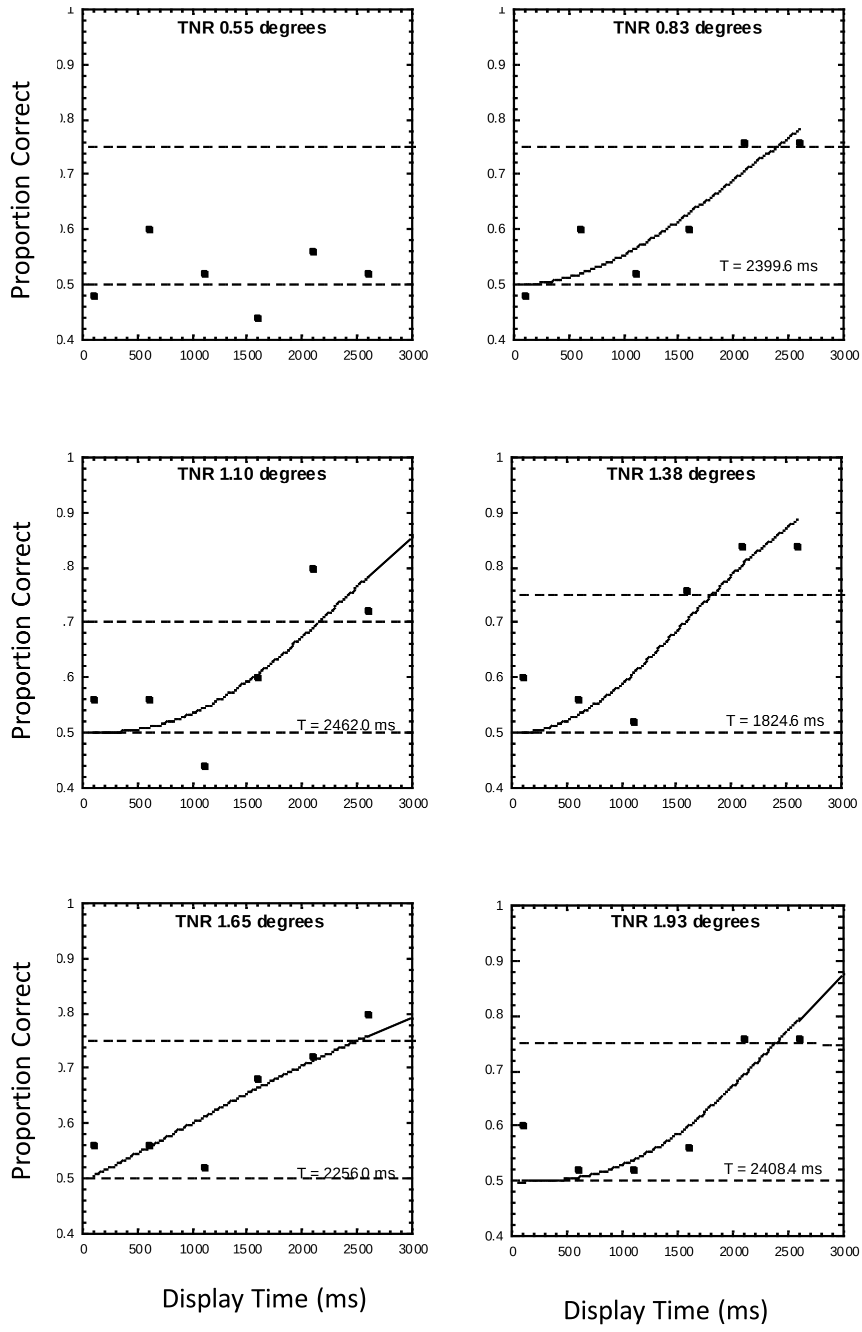
9.0 Appendices

Appendix 1



***Appendix 1: Threshold performances for observer SB-W**. Complete raw data set using times new roman font (TNR) collected from observer SB-W plotted as psychometric functions of reading performance (proportion of correct responses) against statement presentation time (ms). Text sizes ranged from 0.55 degrees to 1.93 degrees.*

Appendix 2: ERP test card passages with Gunning Fog index score.

Nine ERP cards are shown below. Each has a Gunning Fog index score of 9.1. Complex words are words that have three or more syllables, but not including proper nouns, familiar jargon, or compound words. Common suffixes such as -es, -ed or -ing are not included as syllables.

Passage 1

Sharks have lived in the oceans for <u>millions</u> of years. The largest species of shark can grow to over twelve meters in length whilst the smallest to only <u>seventeen centimetres</u>. Most sharks live in the salt water of the oceans, although some sharks found in Asia, swim in fresh water rivers.

Word length = 51, complex words = 3, sentences = 3, Gunning Fog Score 9.1

Passage 2

The warm shallow waters surrounding Australia are the perfect <u>environment</u> for coral to grow. When many coral live <u>together</u> in the same <u>area</u> of ocean it is called a coral reef. A single reef can take hundreds of years to grow and will provide a home for thousands of marine creatures.

Word length = 51, complex words = 3, sentences = 3, Gunning Fog Score 9.1

Passage 3

The third largest ocean on our planet is the Indian Ocean. It stretches for hundreds of miles between <u>continents</u> and covers twenty percent of the earth's surface. Every year storms and <u>hurricanes</u> move across the sea, mauling the islands that are scattered throughout this part of the world with <u>enormous</u> waves.

Word length = 51, complex words = 3, sentences = 3, Gunning Fog Score 9.1

Passage 4

The largest mammal to have lived on earth is the blue whale, with length from fin to nose being thirty meters. The extreme size of whales allowed them to roam the seas unopposed by other marine creatures. However, humans have now hunted the blue whale close to the point of extinction.

Word length = 51, complex words = 3, sentences = 3, Gunning Fog Score 9.1

Passage 5

Seahorses are found in the warmer oceans of the world, where they seek shelter within seagrass habitats. This fish has a unique appearance with an upright body, long snout and curled tail. Seahorses use their tail to anchor themselves within the marine grass, where they become camouflaged and hidden from danger.

Word length = 51, complex words = 3, sentences = 3, Gunning Fog Score 9.1

Passage 6

In the frozen landscape of the South Pole, penguins can be found living in huge family groups. Although these aquatic birds cannot fly, penguins are well adapted for life underwater. They are able to swim quickly through the icy waves, hunting fish and squid to take back to their hungry young.

Word length = 51, complex words = 3, sentences = 3, Gunning Fog Score 9.1

Passage 7

Fresh water marshes with long grass and muddy pools are the perfect home for crocodiles. These reptiles have walked the earth since the time of the dinosaurs and have evolved into expert hunters. With quick reaction times and strong jaws lined with eighty teeth, their prey has little chance of escape.

Word length = 51, complex words = 3, sentences = 3, Gunning Fog Score 9.1

Passage 8

Dolphins live throughout the oceans of the world in family groups called pods. A pod will contain between ten and thirty adults, although much larger pods are found if ample food is available. Dolphins communicate using clicking noises and whistles, leading other dolphins to food or away from danger to safety.

Word length = 51, complex words = 3, sentences = 3, Gunning Fog Score 9.1

Passage 9

The turtle is a prehistoric reptile that can live on land or in the ocean. It can spend several hours at a time under the water, although every eight hours it must resurface to breath fresh air. The largest turtle species has a shell that can measure two metres in length.

Word length = 51, complex words = 3, sentences = 3, Gunning Fog Score 9.1

Appendix 2 continued: Example of an ERP chart with triple line and triple word spacing;

Sharks have lived in the oceans for millions of years. The largest species of shark can grow to over twelve meters in length whilst the smallest to only seventeen centimetres. Most sharks live in the salt water of the oceans, although some sharks found in Asia swim in fresh water rivers.

Appendix 3: Text spacing for ERP test charts

	Single		Double		Triple	
Size of inter-word space	2.5mm	0.36 deg	5mm	0.72 deg	7.5mm	1.07 deg
Size of interline space between lowercase 'x'	5.5mm	0.79 deg	15.5mm	2.20 deg	25.5mm	3.65 deg

Nb. The angular size of the letter or spacing is the corresponding visual angle subtended at the observers' eye.

Angular size in degrees = 57.3 x (Physical Size/Viewing distance)

Appendix 4

Letter of Invitation

Dear Patient,

You have been invited to participate in a research project. The aim of the project is to investigate the best way to present written text to people with macular degeneration.

You do not have to participate in the study, however your involvement will add to the overall knowledge that we have about reading with macular degeneration. The results will hopefully assist people with macular degeneration to improve their ability to read. Your involvement would be very gratefully received.

Your involvement would only involve a one off appointment with Sally Blackmore, who is an optometrist working in Cheltenham Eye Department. The appointment will take no more then one hour and you only need to attend once, at a time that is convenient to you.

If you are interested in participating, please read through this information pack. Sally Blackmore will contact you by telephone to arrange a convenient appointment if you wish to participate and also to answer any questions that you may have.

Kind Regards,

Sally Blackmore BSc (hons) MC Optom

Appendix 5

Reading with Macular Disease

Participant Information Sheet

AIM: Can modifications to standard text spacing be used to enhance reading ability of patients with macular degeneration?

You have been invited to take part in a research study. Please take time to read the following information carefully.

What is the purpose of the study?

Many people with macular degeneration struggle to read. This research study will increase our understanding of how to best present reading material to sight impaired people. Although you may not benefit directly from taking part in this study, your involvement will increase our understanding of the reading problems faced by people with macular degeneration.

Why have I been chosen?

You have been asked to take part in this study because we know that you, like millions of other people in the UK, have had your vision affected by macular degeneration. Many patients from the eye department are going to be asked to contribute in this study and we hope that approximately 30 patients agree to participate.

Who is carrying out the research?

Sally Blackmore is an optometrist working at Cheltenham General Hospital. She is carrying out this research study in conjunction with and under the supervision of Professor S.J. Anderson from the School of Life and Health Sciences at Aston University. The researcher is not being paid to undertake the research.

What will happen to me if I take part?

You will be asked to attend the hospital for an assessment that will last no more than one hour. Your consent to be involved in the study will be taken and a copy of the consent document and a patient information sheet will be given to you. You will have your vision tested by an optometrist and then be asked to read aloud different passages of text. The optometrist will time you as you read the words.

The study involves a single one-off visit to the hospital. No drops will be put into your eyes. If you have any problems after the visit, you can contact Sally Blackmore directly by telephone or email.

Are there any potential risks in taking part in the study?

There is no risk to your eyes or vision from taking part in the study. If you find the test too tiresome, you are free to withdraw from the test at any time.

Do I have to take part?

No. You are free to withdraw from the study at any time and doing so will not affect your treatment within the eye department at this time or in the future.

Can I claim expenses and payments for taking part in the study?

Because the Eye Department is not receiving any funding for this research, we are unable to offer any payment for expenses or for taking part. We will, however, gratefully acknowledge your involvement in the study.

Will my taking part in this study be confidential?

All details of participants involved in the study will be kept confidential. Results from the study will be anonymous - the data collected cannot be linked to any individual who has taken part. All information will be kept on a secure data base and will remain strictly confidential. The data collected will be kept for 15 years before being destroyed.

What will happen to the results of the research?

The results will be published in scientific journals and in the post-graduate thesis of Sally Blackmore. Any publications will maintain our commitment

to confidentiality. Volunteers may request an overview report of the findings from Sally Blackmore.

Who is organising and funding the research?

Sally Blackmore and Professor Anderson are organising the research. There is no funding to support this research.

Who has reviewed the study?

This research has been approved by Aston University's Ethics Committee and South West 2 REC.

Who do I contact if something goes wrong or I need further information?

Sally Blackmore is contactable by email sally.blackmore@glos-nhs.uk

or by telephone 08454 223203

Who do I contact if I wish to make a complaint about the way in which the research is conducted?

If you have any complaints about the study, please contact the secretary of Aston University Research Ethics Committee on j.g.walter@aston.ac.uk or tel 0121 204 4665.

You are under no obligation to take part in this study. If you do agree you are free to withdraw at any time.

Appendix 6

CONSENT

Can modifications to standard text spacing be used to enhance reading ability of patients with macular degeneration?

Chief Investigator: Sally Blackmore

I confirm that I have read and understood the information sheet for the above study.

Signature…………………..

Print name………………… Date…….

I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

Signature…………………..

Print name…………………Date…….

I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, and without my medical care or legal rights being affected.

Signature…………………..

Print name…………………Date………

I agree to take part in the above study:

Signature………………….

Print name…………………Date……..

Copy 1 Retained by SB

Copy 2 Retained by Participant

Appendix 7: Power Table

Power analysis table. (York University, CA 2010)

Power analysis for ANOVA designs

3x 3 layout; Alpha= 0.050

DELTA (in units of sigma=Std. Dev.)

N	0.250	0.500	0.750	1.000	1.250
2	0.060	0.093	0.152	0.240	0.355
3	0.068	0.128	0.239	0.397	0.579
4	0.076	0.163	0.323	0.534	0.738
5	0.083	0.199	0.404	0.648	0.844
6	0.091	0.235	0.481	0.740	0.911
7	0.099	0.271	0.551	0.812	0.950
8	0.107	0.308	0.616	0.866	0.973