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Crowding in visual acuity tests: unravelling the relative roles of optotype separation, gaze control and attention in children and adults

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ABSTRACT

FACULTY OF SCIENCE AND TECHNOLOGY

CROWDING IN VISUAL ACUITY TESTS: UNRAVELLING THE RELATIVE ROLES OF OPTOTYPE SEPARATION, GAZE CONTROL AND ATTENTION IN CHILDREN AND ADULTS

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The measurement of visual acuity in children is important to detect visual anomalies including amblyopia. The use of visual acuity tests that induce ‘crowding’ are often recommended despite little standardization of the features in such tests. In addition, crowding in children’s foveal vision is known to be greater in extent than in adults and to be influenced by the nature of the flankers. This thesis presents new evidence that foveal crowding in children and amblyopic adults with strabismus is greater for letter acuity tests which require accurate gaze control and where the similarity of target and flankers imposes a greater attention demand. A slower maturation of crowded than single optotype acuity in young children is also shown.

Using commercially available children’s acuity tests, the first study of this thesis showed that greater foveal crowding occurred with smaller inter-optotype spacing and with letter rather than picture optotypes. A decrease in crowding, resulting in improved visual acuity between the ages of 4 and 9 was also shown. In order to follow up these initial results, custom-designed visual acuity tests were produced to disentangle the contributions of contour interaction, eye movements and attention to the overall crowding effect. The second study in this thesis showed that crowding is greater with linear rather than single letter presentation and with letter rather than bar flankers in young children (aged 4-6), but not in adult controls. In a further study using a sample of amblyopic adults with strabismus more crowding was observed with linear presentation of letters and letter rather than bar flankers, a result consistent with the results seen in young children.

These findings improve our understanding of crowding in children and in strabismic amblyopia and can be used to improve the standardizing of crowded acuity measurement and have the potential to increase the sensitivity of visual screening for amblyopia.

Key words: Children’s vision, visual crowding, vision screening, visual development, amblyopia

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1.1 Introduction

1.1.1 Context of the research

Screening programmes aim to identify individuals at risk of a treatable disease at an age where treatment is effective (Hall and Elliman, 2003). The primary aim of vision screening in children is to detect the presence of amblyopia and its risk factors (National Screening Committee, 2013). Amblyopia is a relatively common developmental disorder of the visual system where early detection and intervention can prevent loss of visual function and binocularity. Amblyopia is associated with strabismus (mis-alignment of the visual axes), anisometropia (unequal refractive error) and visual deprivation (Holmes and Clarke, 2006). One aspect of vision which is often abnormal in amblyopia is crowding, or the ability to recognize an object in the presence of clutter (Flom, 1991, Levi, 2008). Much of the crowding research in recent years has focussed on the development of theories of crowding and has in large part used laboratory based studies of peripheral vision [for reviews see Pelli (2008), Levi (2008)]. In the context of vision screening, foveal crowding in a clinical context is of more interest. The increased crowding often seen in amblyopia can be exploited in screening programmes by using visual acuity tests with crowding features to amplify the difference in acuity between amblyopic and normal observers. The first study in this thesis provides corroborative evidence that in children, crowded visual acuity tests do not all give the same measurement of visual acuity for a give letter size because of variation in crowding features and stage of development of the child. The second study provides new evidence in the understanding of foveal crowding and its components (contour interaction, gaze control and attention) by demonstrating the impact on visual acuity of varying the relative contributions of each of these components in normally sighted children and adults. The third study shows how the relative contributions of the components of crowding affect visual acuity in adults with strabismic amblyopia. The new evidence presented in these studies enables recommendations to be made for the design of screening tests to best detect amblyopia.

1.1.2 Introduction to the literature review

This chapter will review the literature relevant to this thesis. The first section, on vision screening will set the research in a clinical context, outlining the importance of visual acuity measurement as a screening tool for children. Unspecific national guidelines on which acuity test is best for screening children highlights the need for research into the suitability and comparability of different tests for different age groups (National Screening Committee, 2013).

Section 1.3 explains visual resolution and its limitations by optical and neural factors. Section 1.4 reviews how visual acuity is measured, showing why the traditional Snellen chart has been superseded, at least for research, by logMAR based tests, such as the Bailey-Lovie and ETDRS charts. Modifications to adult charts to improve testability in children led initially to use of single optotype tests, but these were found to lack sensitivity to detect amblyopia, so the section reviews commonly used crowded children's tests. Full reviews are available (Fern and Manny, 1986, Friendly, 1978, Anstice and Thompson, 2014). The lack of standardization of crowding features in these tests is discussed.

The next section, 1.5, reviews how vision develops in children, showing that letter recognition in more complex displays reaches maturity later than recognition of single letters. It has been suggested that unsteady fixation or inaccurate saccadic eye movements may play a role in the slower maturation of line acuity, so the development of these eye movements is included. The section also reviews aspects of the development of attention, which affects a child's ability to select a target from background distractors; for reviews, see Desimone and Duncan (1995) and Atkinson and Hood (1997).

Section 1.6 introduces visual crowding and explains the use of the term in this thesis to include the effects of contour interaction, gaze control and attention and section 1.7 summarizes the theories of crowding; for reviews see Levi (2008) and Pelli (2008). Although many of the theories have been developed from studies of the adult peripheral retina, it is argued that the same theories could apply to the immature fovea. Section 1.8 looks at the specific case of foveal crowding in children; for review see Huurneman et al. (2012). The extent of crowding has been found to be greater in children than in adults; some young children are thought to have larger crowding because of immature control of eye movements and there is some evidence that attentional factors such as those seen in adult peripheral crowding are present in children's foveal crowding.

Amblyopia can result from an impairment of the developing visual system and features abnormally large crowding. Section 1.9 reviews the prevalence, definitions and implications of amblyopia and discusses the deficits at various levels of the visual system in the main types of amblyopia; for reviews, see Barrett et al. (2004), Kanonidou (2011), Wong (2012) and Birch (2013). Recent changes in treatment offer hope of improvement to not only visual acuity, but also stereopsis, and is now possible beyond the critical period of development. However, detection of amblyopia at a young age still remains important.

The research questions are stated in section 1.10.

1.2 Vision Screening

Screening is defined by the UK National Screening Committee as ‘a process of identifying apparently healthy people who may be at increased risk of a disease or a condition. They can then be offered information, further tests and appropriate treatment…’ (National Screening Committee, 2015). The most common reasons for reduced vision in children are amblyopia and its principal risk factors, strabismus and significant refractive error, although other pathological conditions can result in reduced vision (Lola Solebo and Rahi, 2014, Simons, 1996). As amblyopia and refractive error are both treatable, screening can be worthwhile, if the screening tools are accurate. A basic criterion for a screening test, defined by Wilson and Jungner, is that it should be valid, repeatable, sensitive and specific (Wilson and Junger, 1968)

Timely detection of reduced vision will optimise the effectiveness of intervention (Solebo et al., 2014, Holmes et al., 2011, Logan and Gilmartin, 2004, Birch, 2003, Stewart et al., 2004). If amblyopia or strabismus is left undetected, or untreated, school performance can be affected, along with self-image and fine motor skills and there is an increased risk of visual impairment in the event of damage to the fellow eye (Birch, 2013, Carlton and Kaltenthaler, 2011). Furthermore, career choices can be limited (Webber and Wood, 2005).

Although there has been some controversy regarding the cost-effectiveness of universal vision screening in childhood (Snowdon and Stewart-Brown, 1997, Hall and Elliman, 2003), studies have demonstrated that screening with subsequent treatment is effective in terms of clinical outcome (Clarke et al., 2003, Williams et al., 2003, Kvarnström et al., 2002, Williams et al., 2002, Ohlsson et al., 2001). Two reviews of vision screening have concluded that lack of normative data in age appropriate tests, variable definitions of amblyopia and poor methodology in trials made it difficult to draw conclusions about the effectiveness of vision screening to detect amblyopia (Powell and Hatt, 2009, Schmucker et al., 2009). Therefore, in order for clinicians to argue successfully in favour of vision screening, the tests used need to be better understood, comparable and standardized.

In 2013, the National Screening Committee, responsible for health screening programmes in the UK, rationalized the nationwide childhood screening programme. Although a range of clinical tests is necessary for diagnosis of most ocular conditions, current childhood vision screening guidelines in the UK rely only on measurement of visual acuity to distinguish those children for whom further tests are indicated (Lola Solebo and Rahi, 2014). Current guidelines recommend an orthoptist-led programme, whereby all children aged 4-5 should have a measurement of vision in each eye by using a crowded logMAR chart (National Screening Committee, 2013). There is no guideline on which test to use and the report cites a lack of evidence on ‘comparable precision between charts’.

In the US, guidelines are more specific. The Paediatric Eye Disease Investigator Group (PEDIG) developed the Amblyopia Treatment Study (ATS) protocol to enable visual development of children aged 3-6 to be measured using a standardized protocol- crowded HOTV optotypes in a staircase method (Holmes et al., 2001). The ATS protocol was found to have good testability and repeatability (Holmes et al., 2001), but to over-estimate vision by just under a line compared with the ETDRS chart in children aged 5-12 (Rice et al., 2004). A recent article has proposed new best practice guidelines for vision screening in the US and recommends screening of 3-6 year old children based on either visual acuity testing or on instrument screening (autorefractor or photoscreening)(Cotter et al., 2015). The recommended visual acuity tests are single, surrounded HOTV letters or Lea symbols surrounded by crowding bars. Normative data are available for the HOTV test (Pan et al., 2009, Drover et al., 2008) and while not population based, there are some normative data for the Lea Symbols (Dobson et al., 2003, Becker et al., 2002).

So there is an established need for visual acuity tests in vision screening but some debate about the efficacy of their use. There is some evidence that screening children younger than the currently recommended age of 4-5 improves outcomes (Williams et al., 2003), but measuring visual acuity in younger children can be more problematic and amongst the age-appropriate tests available, there is much variability in design and features. More evidence about the effects of design and comparability of tests at different ages will make it easier to show that screening can improve the successful detection and timely treatment of amblyopia. These gaps in knowledge have led to the development of research questions 1 and 2 (section 1.10)

1.3 Visual acuity and its limitations

1.3.1 Definitions

Visual acuity may be defined as the detection, resolution and recognition ability of the visual system (Bennett and Rabbetts, 1998). Distinct from visual acuity, which reflects the ability to recognize components as separate, the visual system also has the ability to localize components relative to one another, known as hyperacuity (Westheimer, 1975). Hyperacuity is applied in such tasks as Vernier acuity, bisection acuity, stereoacuity and displacement detection. Hyperacuity thresholds can be substantially lower than visual acuity thresholds, in the order of 5-10 seconds of arc (Westheimer, 2009). It is, however, visual acuity and its limitations which are of interest in this thesis.

1.3.2 Rayleigh's criterion

A point source of light is imaged on the retina as a 'point spread function', governed in its central part by diffraction and in its periphery by light scatter (Ginis et al., 2012).

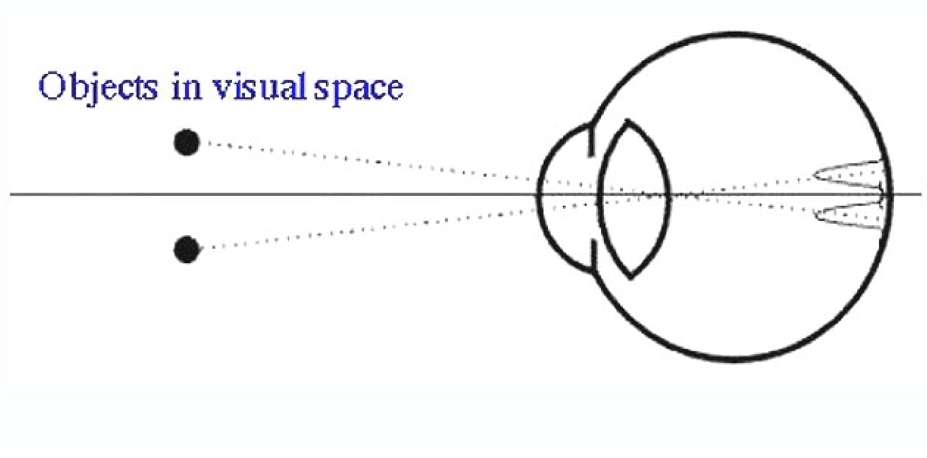


Figure 1.1 after Kolb et al. (1995), showing 2 point sources and their point spread functions on the retina.

For two points in the visual field to be just resolved as separate, the Rayleigh criterion needs to be satisfied (Figure 1.2). This states that for resolution of 2 points, the peak of one point spread function needs to be on the first trough of the second function.

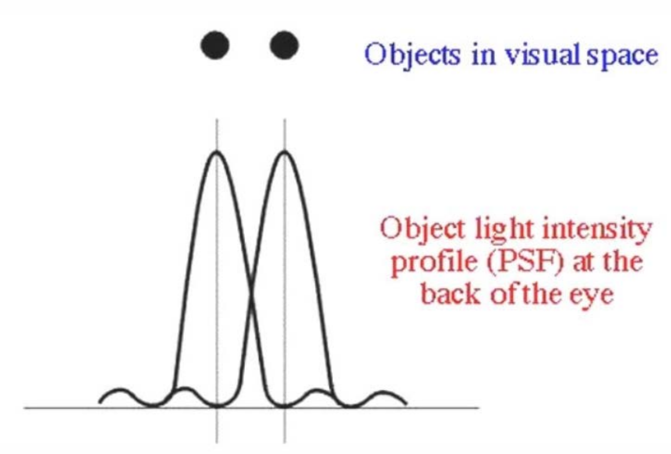


Figure 1.2 Raleigh's Criterion, after (Kolb et al., 1995), showing the overlap of the spread in light distribution from two point sources. For these to be perceived as separate, there needs to be a dip in the distribution equal to around half of its width.

1.3.3 Retinal limitations to resolution

Resolution is governed by both photoreceptor and ganglion cell density (Rossi and Roorda, 2010). Visual acuity is highest in the centre of the fovea, with a decline in resolution with eccentricity. This is because of a decrease in density of foveal cones as well as a change in post-receptor organization on moving away from the fovea (Green, 1970).

To resolve a sine wave grating, it needs to be sampled at a minimum of 2 points on the cycle. The number of points per degree of visual angle which sample an image will therefore determine the spatial frequency that can be resolved (De Valois and De Valois, 1988). In a sample of 8 human enucleated eyes, Curcio et al. (1990) measured centre-to-centre cone spacing in the fovea to be 2.55µm on average. Peak foveal cone density was found to be very variable (98,000 to 324,000/mm^2), but the total number of cones within 1 mm of fixation was found to be relatively constant between eyes, supporting a theory of variation in extent of lateral migration of cones towards the foveal centre during development (Hendrickson and Yuodelis, 1984, Yuodelis and Hendrickson, 1986). More recent *in vivo* studies using optical coherence tomography (OCT) have shown that, during development, central migration of cones together with their elongation increases central packing density without an overall increase in number of cells (Provis et al., 2013).

A cone spacing of 2.5μm yields a theoretical maximum resolution of 66 cycles/degree, which is higher than the 30-60 cycles/degree (Snellen acuity 6/6-6/3) found in most psychophysical studies (Sloan, 1968, Westheimer, 1981), suggesting limitations other than cone spacing. More recently, Rossi and Roorda (2010) used adaptive optics and psychophysical methods to compare cone spacing and resolution across the fovea. The adaptive optics minimized blur and aberrations to allow comparison of retinal limitations. They found that at the foveola centre, resolution was limited by cone spacing, but that immediately outside the centre, resolution was better predicted by sampling of retinal ganglion cells.

1.3.4 Optical Limitations to resolution

Other factors which limit resolution include aberrations, light scatter within the eye, pupil size, illumination and refractive error. Larger pupil sizes increase illumination but result in aberrations of greater magnitude, whilst smaller pupils reduce aberrations, but also reduce illumination and increase diffraction. A pupil size of 2-3 mm is optimal for eyes corrected for refractive error, as it gives the optimal balance between these factors (Atchison et al., 1979).

Uncorrected refractive error causes a lateral spread of the point spread function, which reduces the eye's ability to resolve two points as separate. The relationship between visual acuity and optical defocus is shown in Figure 1.3.

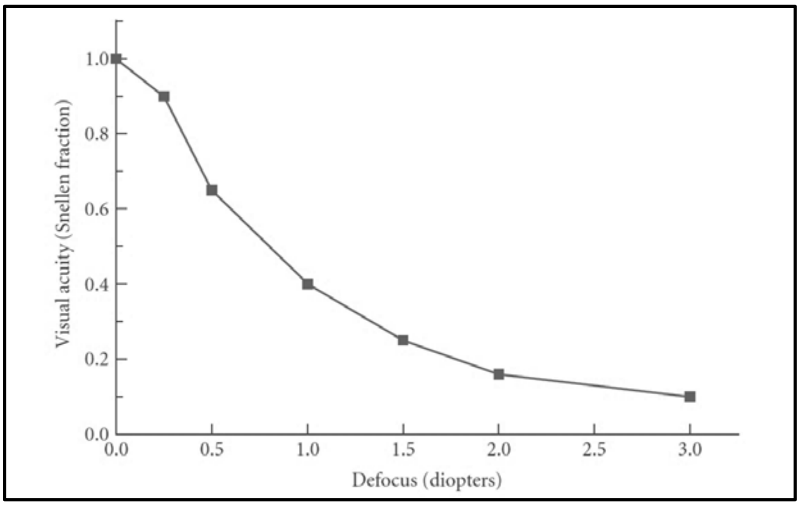


Figure 1.3, after Westheimer (1975), showing the effect of optical defocus on visual acuity.

For high contrast letters, visual acuity is relatively constant for levels of illuminance of around 10 cd/m^2 and higher (Westheimer, 1975). Below levels of 1 cd/m^2, rods take over from the cones and resolution falls to around 5 cycles/degree because of the relatively wider separation of rods than foveal cones and the greater spatial summation (De Valois and De Valois, 1988).

1.4 Measurement of visual acuity

1.4.1 Traditional measures of visual acuity

Visual acuity (VA), is typically measured by recognition of black letters on a white background (Friendly, 1978, Sloan, 1951, Bennett, 1965). Standardized symbols for testing vision are known as optotypes. Traditionally, optotypes are arranged on a chart in rows with each subsequent row containing smaller letters. Many variants of the traditional chart, developed by Snellen in 1862, have emerged, including presentation of letters on computer screens or tablets or in booklet form and with letters presented in isolation or in isolated rows. In addition, a large variety of non-letter targets have been used as optotypes (Fern and Manny, 1986, Friendly, 1978, Keith et al., 1972).

Alternatives to measuring visual acuity through ‘recognition acuity’ are gap resolution acuity, for example with the Landolt ring or the Broken Wheel Test (Richman et al., 1984) or grating acuity with the Teller Acuity Cards (Mayer et al., 1995, Drover et al., 2009). The Landolt ring is the reference optotype in the International Visual Acuity Standard (International Council of Ophthalmology, 1984) and its main advantage is that there is only one element of detail, the variation being in orientation of the optotype. However, its legibility has been found to be lower than other letters (Grimm et al., 1994, Rassow and Wang, 1999, Latham et al., 2014). The international standard also accepts Sloan letter optotypes for clinical visual acuity measurement.

There are a number of limitations of measuring visual acuity with the Snellen chart that can impact the measurement (Sloan, 1980, Wick and Schor, 1984). The number of letters on each line and the spacing between the letters is not constant, thus creating varying levels of difficulty between the lines, other than the decreasing angular subtense of letters. Legibility of the letters is not standard, making incremental differences between the lines hard to measure. Furthermore, the progression of letter size between the lines does not change systematically, resulting in the lack of an accurate scoring system (McGraw et al., 1995) and poor repeatability (Gibson and Sanderson, 1980).

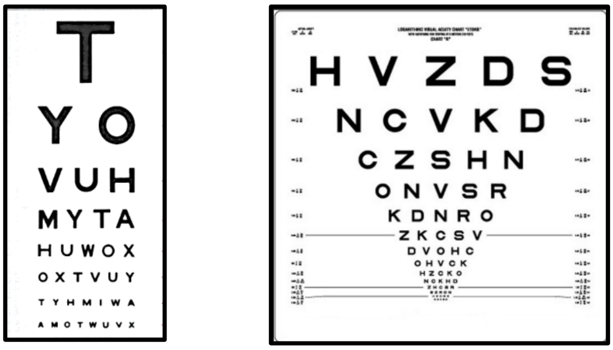


Figure 1.4 The Snellen chart and the ETDRS chart (Ferris et al., 1982)

1.4.2 Bailey-Lovie design principles for test charts

In 1976, Bailey and Lovie developed new design principles for visual acuity measurement, namely that there should be the same number of optotypes of each size on each row and that the optotypes should have equal legibility; letter size should vary in a logarithmic manner and specified in logMAR (the log of the minimum angle of resolution); the spacing between optotypes and rows should be proportional to optotype size (Bailey and Lovie, 1976). In 1980, the Committee on Vision of the National Research Council also made recommendations for design principles of charts (National Academy of Sciences-National Research Council Committee on Vision, 1980). The relevant British standard, BS 4274-1 (2003) recommends the letter set C, D, E, F, H, K, N, R, P, U, V, Z constructed on a 5x5 grid, and recommends an inter-letter spacing of one letter width (British Standards Institute, 2003).

The Bailey-Lovie principles and some of those of the NAS-NRC were adopted in the development of the Early Treatment of Diabetic Retinopathy Study (ETDRS) chart (Ferris et al., 1982), which is now widely recognized as the gold standard for VA measurement in research (Figure 1.4). Many of the inadequacies of the Snellen chart have been overcome in the design of the ETDRS chart: letter-by-letter scoring allows accurate, standardized scoring; visual acuity can be measured in people with poor vision, as each line contains 5 letters. These are chosen from the Sloan letter set: C, D, H, K, N, O, R, S, V and Z, constructed on a 5x5 grid. A geometric progression of letter size (1.26x) and inter-letter spacing proportional to letter size increases repeatability (Ferris et al., 1982, Ricci et al., 1998, Raasch et al., 1998). Testing distance can be reduced if vision is poor with 0.3 logMAR added when the distance is halved. The ETDRS chart has been found to be accurate and repeatable in children from the age of 6 (Manny et al., 2003).

1.4.3 Measurement of children's vision

Particular problems are encountered when measuring vision in children younger than 6 years (Fern and Manny, 1986, Friendly, 1978, Keith et al., 1972). Pre-school children may not be able to name letters, especially in the upper case form found on most vision charts; they may lack the attention span needed to complete the test, or the motivation to co-operate (Anstice and Thompson, 2014, Friendly, 1978).

In order to overcome some of these problems and improve the testability of young children, modifications to adult charts have been made. Letters can be presented singly, or in an isolated row in order to keep the child's attention on a simpler task (McGraw et al., 2000). For pre-literate children, pictures can be used instead of letters and for infants, preferential looking can be used, whereby the child's preference to look at a picture of a familiar object rather than a blank card of equal luminance is observed (Mayer and Dobson, 1982). A recognition task can be turned into a matching task, whereby the child is required to match the letter on a distant chart to one on a card in front of them (Hedin et al., 1979, Simons, 1983), although a matching test relies on cognitive function, the variability of which can confound the results (Anstice and Thompson, 2014).

Unfortunately, many of these modifications have led to children’s tests not fulfilling the Bailey-Lovie principles. The simplest modification, recommended by Keith et al. (1972), of presenting letters or symbols in isolation was found to over-estimate visual acuity, compared to Snellen acuity, especially in amblyopes (Hilton and Stanley, 1972, Youngson, 1975, Flom, 1991). Hilton and Stanley (1972) in a study of 75 amblyopic children found better acuity with single letters than using a Snellen chart. The differences between single letter and Snellen acuity varied, averaging around 3 lines, but reaching as much as 6 lines in some children. Clearly, single optotype acuity as a screening tool for amblyopia detection would generate many false negatives.

Picture optotypes generate interest in young children but can be difficult to standardize (Simons, 1983, Fern and Manny, 1986). It can prove challenging to produce a set of pictures with equal legibility. Furthermore, pictures are often more complex in shape than letters and pictures can become antiquated and less recognizable as objects change, such as the telephone in the Allen pictures (Friendly, 1978, Allen, 1957).

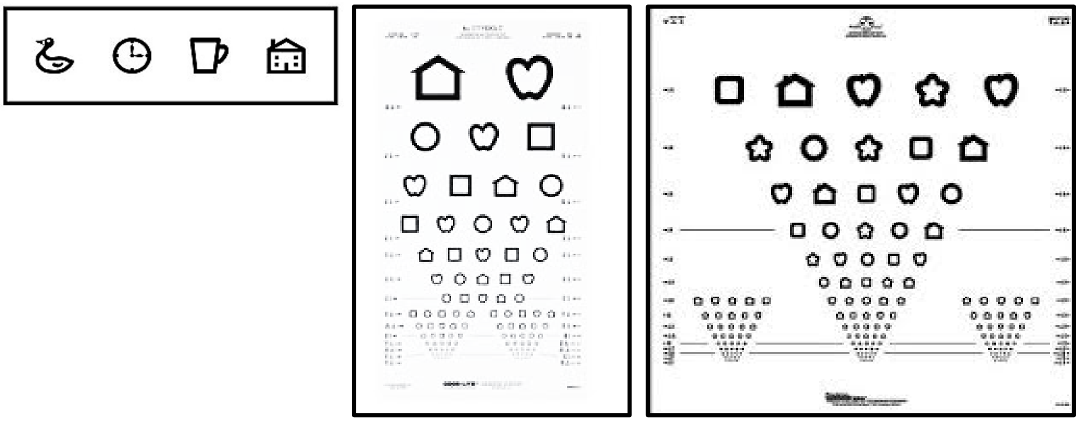


Figure 1.5 shows example presentations of the Crowded Kay Pictures Test
the Lea Symbols and the Patti Pics Vision Testing System

Three commonly used picture tests, available in crowded format, are the Kay Pictures Test (Kay, 1983), the Lea Symbols (Hyvärinen et al., 1980) the and Patti Pics Vision Testing System (Mercer et al., 2013) (Figure 1.5). The Kay Picture optotypes were based on objects that would be familiar to young children and were constructed with the same stroke width as the Snellen equivalent, but with variations in shape and intricacy. The size of the optotypes was derived empirically, each picture optotype being twice the equivalent Snellen letter size to account for the more intricate shapes of the pictures compared to letters. Several studies (Jones et al., 2003, Elliott and Firth, 2007) have shown the Kay Pictures Test to slightly over-estimate acuity compared with the logMAR Crowded Test. The Crowded Kay Pictures Test was also found to be less sensitive to detection of astigmatic blur than the logMAR Crowded Test (Little et al., 2012). The Lea Symbols use optotypes which can be readily recognized by young children (house, apple, square and circle), have contours more similar to letters and all blur to look like a circle below threshold acuity (Becker et al., 2002). Optotype size was originally derived empirically, but later calibrated to the Landolt C test (Vision in Preschoolers Study Group, 2003). A comparison of the Lea

Symbols with the Bailey-Lovie Chart (Dobson et al., 2003) again indicates an over-estimation of acuity by the picture optotypes of about one line. Grading of size is in logarithmic steps for both tests. The Patti Pics optotypes are similar to the Lea Symbols, but also contain a star. They are slightly smaller than the equivalent Lea Symbols and perhaps for this reason show better statistical agreement with Sloan letters (Mercer et al., 2013). However, Candy and colleagues showed greater variability of optotypes discrimination within the set of Patti Pics optotypes than within the Lea Symbols (Candy et al., 2011).

Several letter tests have been designed to have greater testability than traditional charts and are available in logMAR form: the logMAR Crowded Test, formerly the Glasgow Acuity Cards (McGraw and Winn, 1993), the Sonksen logMAR Test, (Salt et al., 2007) and the HOTV Test (Holmes et al., 2001). Both the logMAR Crowded Test and the Sonksen logMAR Test comprise rows of letters surrounded by a bar of one stroke width, but the separation of letters varies between tests; for the logMAR Crowded test, it is 0.5 letter-widths and for the Sonksen test, it is 1.0 letter-widths. The HOTV Test presents letters singly with bar surrounds, the bars being equal in length to the height and width of the letter and one letter width distant. The Sonksen Test comes with monocular and binocular age norm data in centile form (Sonksen et al., 2008), allowing practitioners to judge if acuity measured with this test is appropriate for a child's age. Normative data are available for the HOTV Test (Pan et al., 2009). The logMAR Crowded Test has been shown to agree with the Bailey-Lovie Chart in adult observers (McGraw et al., 2000) but has limited normative data for children (Langaas, 2011).

Two electronic versions of the ETDRS Chart have been developed for use with children, the E-ETDRS (Beck et al., 2003) and the COMPLog Clinical Visual Acuity

Measuring System (Laidlaw et al., 2003). Both have adopted different presentations of letters in order that acuity should be comparable to the original chart: in the E-ETDRS, the letters are presented singly with surrounding crowding bars placed one letter distant and in the COMPlog system, letters are presented in lines with an inter-letter spacing of half a letter width and a surrounding crowding box at 1 letter width distance, although these parameters can be varied. These different presentations of the target letters represent different levels of task difficulty which may be expected to produce different results in patients with amblyopia or other disorders, or in children (Bailey and Lovie-Kitchin, 2013). Table 1.1 overleaf shows the array of formats used in crowded children's tests.

Table 1.1 compares design and format of 6 paediatric visual acuity tests which are available in crowded logMAR format, with the ETDRS Chart for comparison

Test	**optotypes**	**optotype size**	**crowding**	**spacing** (optotype widths)
Kay Pictures	8 pictures	2x ETDRS equivalent	Line of 4 pictures box surround	0.5
Lea Symbols	4 symbols	1.5 x ETDRS equivalent	i) chart format- 5 symbols/line ii) line of 4 symbols- box surround iii) isolated symbols-bar surround	i) 1.0 ii)1.0 between symbols 0.5 to box iii) 0.5
Patti Pics	5 symbols	As ETDRS	Chart format 5 symbols/line	1.3
Crowded logMAR	X V O H U Y letters	As ETDRS	Line of 4 letters box surround	0.5
Sonksen	X V O H U T letters	As ETDRS	Line of 4 letters box surround	1.0
HOTV	HOTV letters	As ETDRS	i) Linear chart- 5 symbols/line ii) line- box surround iii) isolated symbols-bar surround	i) 1.0 ii)1.0 between symbols 0.5 to box iii) 0.5
ETDRS	CDHKNORSVZ Sloan letters		Chart format	1.0

A recent review of children's acuity tests (Anstice and Thompson, 2014) cautions against comparing measurements between tests because observed acuity changes may reflect differences in chart design rather than true changes in visual function. The authors call for uniform principles to be adopted in paediatric test design. Research questions 3-5 arose from the need for greater understanding of the effect of crowding features on visual acuity measurement in children.

1.4.4 Repeatability of visual acuity measurements

Estimation of visual acuity using a letter chart can be imprecise as an individual will often read some letters of a certain size correctly and misname others (Carkeet et al., 2001). The repeatability of a test will determine its ability to detect a change in visual acuity between measurements, a metric important to detecting pathology, monitoring the success of interventions, monitoring visual development and in determining the number of subjects needed in clinical trials (Hazel and Elliott, 2002, Reeves et al., 1987, Gordon et al., 1998). Studies of repeatability of visual acuity measurement in adults (Lovie-Kitchin and Brown, 2000, Siderov and Tiu, 1999, Arditi and Cagenello, 1993, Bailey et al., 1991, Hazel and Elliott, 2002) and children (McGraw et al., 2000, Manny et al., 2003) have yielded repeatability of around 1-2 lines in normally sighted observers, although as Reeves et al. (1987) point out, there is less variation between subsequent measures in a population of normally sighted people than in those with an abnormality. Poorer repeatability has been found in an adult low vision population (Woods and Lovie-Kitchin, 1995) and in children with reduced vision (Kheterpal et al., 1996) and Flom (1986) found a shallower slope in the frequency-of-seeing curves of amblyopic than normal eyes, inferring poorer repeatability.

Visual acuity tests which show better repeatability in normally-sighted adults are those with logarithmic progression of letter sizes, letter-by-letter scoring, and equal number of letters of each size presented (Raasch et al., 1998). Less is known about the effect of test design features on repeatability in children’s visual acuity tests, which has led to the development of research question 6.

1.5 Development of the Visual System

1.5.1 Development of visual acuity

Vision in the new-born human is blurred and indistinct but develops rapidly over the first six months (McCulloch, 1998, Atkinson and Braddick, 1982). It is difficult to know when vision becomes adult-like because its measurement generally demands a response from the child, which involves other developing mechanisms, such as attention, behaviour and communication (Leat et al., 2009). An objective technique, Pattern Visually Evoked Potential (VEP), uses electrodes placed on the scalp to measure acuity in children of any age by recording the response amplitude over a range of spatial frequencies. Acuity measured in this way is higher than that from behavioural methods such as preferential looking, until the age of about a year (Leat et al., 2009).

After the first six months of rapid development, acuity then continues to develop more slowly, becoming adult-like at around 5-6 years if measured by preferential looking (Mayer and Dobson, 1982, Birch et al., 1983) or single optotype recognition (Simons, 1983, Sheridan, 1974, Smørvik and Bosnes, 1976, Woodruff, 1972). Acuity is worse if measured with surrounded optotypes, showing a later maturation of crowded acuity (Langaas, 2011, Pan et al., 2009, Sonksen et al., 2008, Drover et al., 2008, Morad et al., 1999, Fern and Manny, 1986, Simons, 1983, Hohmann and Haase, 1982), although see Kothe and Regan (1990). Table 1.2 shows suggested age of maturation of children's vision. The variation in conclusions can be as a result of sample size, methodology and test used. Furthermore, the rate of change in acuity slows with age, making it difficult to define the point at which adult levels of vision are reached.

Table1. 2 shows studies of VA development in children, where letter or Landolt C targets were used.

Author	Test	Age of maturation
Atkinson and Braddick (1982)	Crowded Landolt C	Not adult-like at 5 years
De Vries-Khoe and Spekreijse (1982)	Landolt C	Around 8-10 years
Drover et al. (2008)	Crowded HOTV	Between 7 and 8-10 year old groups
Langaas (2011)	Crowded logMAR	Around 9-10 years
Pan et al. (2009)	Crowded HOTV	Beyond 6 years
Sonksen et al. (2008)	Sonksen logMAR test (binocular)	Around 8 years
Stiers et al. (2003)	Landolt C	Not adult-like at 5 years

The limitations to visual acuity in the younger child could be accommodative, optical, retinal or cortical. Studies of the development of accommodation show that most children are able to accommodate accurately before 12 months of age (Haynes et al., 1965, Braddick et al., 1979, Banks, 1980, Howland et al., 1987). Furthermore, Carkeet has shown the optical quality of 4-6 year olds to be as good as adults (Carkeet et al., 2003), so continued improvement in vision beyond that age is likely to represent development in retinal or cortical areas.

Morphological study of the human fovea at 45 months shows adult-like cone diameter but cone outer segment length and packing density of cones only half of the adult values (Yuodelis and Hendrickson, 1986). Continued development of single optotype acuity beyond this age could therefore reflect development at retinal level.

Continued improvement of crowded acuity beyond single optotype acuity may reflect maturation of higher levels of the visual system, as crowding is a cortical phenomenon (Flom et al., 1963a). Development of the visual cortex is hierarchical, with areas controlling basic functions, mediated by the deeper areas of the primary visual cortex (V1), reaching maturity first, followed by higher functions mediated by extra-striate areas beyond V1 (Kozma et al., 2001).

Analysing a complex scene requires ‘grouping’ of objects by location, or similarity of properties, alongside the opposite process of perceptual analysis- dividing the visual scene to define objects for analysis (Treisman, 1982). This first process of grouping, or integration is thought to be mediated by long-range horizontal connections over the visual cortex, which have been shown to develop throughout childhood (Kovács et al., 1999, Kaldy and Kovacs, 2003). The inverse process of segregation is also thought to occur in extra-striate areas (Allen et al., 2009), with analysis of different image attributes having different timescales for maturation, for example luminance defined optotype recognition is adult-like by 12 years, whereas texture-defined recognition continues to develop beyond 12 years (Bertone et al., 2010). It follows that visual acuity measured using more complex targets which require higher level processing may be expected to show maturity later than is the case for simple targets.

1.5.2 Development of eye movement control

Saccades are the quick movements of the eyes that bring the object of attention onto the fovea. The latency in initiating a saccade decreases until around age 15 (Irving et al., 2006, Luna et al., 2004, Fischer et al., 1997), although studies are not consistent in their conclusions about changes in saccade accuracy or velocity with age (Luna et al., 2008).

Fixation is the ability to keep a steady image on the fovea. It is not passive, but active, requiring constant, small corrective movements, or microsaccades (Luna et al., 2008). The ability to maintain steady fixation has been shown to improve between the ages of 4 and 15, with improvements stemming from longer fixation time around the target and fewer intruding saccades (Ygge et al., 2004, Aring et al., 2007).

As children learn to read, changes in their eye movement behaviour are noted: fixations per line are fewer in number and shorter in duration, saccades are longer and there are fewer regressive, or backwards saccades (Reichle et al., 2013, Rayner, 1986). Coupled with these findings, an improvement in the visual span (the number of characters read in one fixation) with age is noted (Kwon et al., 2007, Rayner, 1986).

These findings showing the development of eye movements in school aged children suggest that younger children may not perform with the same degree of accuracy as older children and adults when performing acuity tasks near threshold; line acuity may be reduced by inaccurate saccades and even single letter acuity may be reduced by poor fixation.

1.5.3 Development of visual attention

When we attend to an object in the visual field, we fixate, or foveate it, placing the image on the fovea, usually with a resultant eye movement. A shift in attention can be driven by the appearance of an object (exogenous) or by internal motivation (endogenous) (Atkinson and Hood, 1997). The allocation of attention is driven by conscious, behaviour-led ‘top down’ control, coupled with a sub-conscious ‘bottom up’ mechanism driven by the appearance of stimuli in the visual field (Wang et al., 2015, Desimone and Duncan, 1995). Improvements in visual search during childhood suggest development of top-down attentional control (Hommel et al., 2004).

Selective attention has been defined as the ability to select items for attention (He et al., 1996, Intriligator and Cavanagh, 2001). This ability to ignore distracting information improves with age and is thought not to mature before 7-10 years (Enns and Akhtar, 1989, Goldberg et al., 2001). It is forced by limited capacity to process all the information in the visual field, resulting in some visual information being disregarded (Desimone and Duncan, 1995). The extent of this spatial resolution has been investigated using targets in the presence of flankers in tracking or reaction time paradigms and has been found to decrease continually throughout childhood (Pastò and Burack, 1997, Wolf and Pfeiffer, 2014, Enns and Girgus, 1985). Later maturation of visual attention has been found where the distractor and target differ by a conjunction of features, such as size or colour, than by a single feature and also in the ability to voluntarily shift attention from object to object (Trick and Enns, 1998).

An area of the visual system has been found to become active where strings of letters which could form words are grouped together in a chunk (Posner and Rothbart, 2000). This cortical area is not activated by strings of consonants and is not present in early readers but is found to a limited degree in 10 year olds, another example of continued development of higher cortical areas well into childhood.

The ability to guess correctly the number of items in a display without counting them, subitizing, is thought to be performed by a pre-attentive mechanism (Trick and Pylyshyn, 1993). It is present for small arrays in 2 year olds (Starkey and Cooper, 1995) and continues to improve throughout childhood (Halberda and Feigenson, 2008). Subitization may have a role in the success of reading a display of multiple optotypes. The magnitude of errors in fixation or saccades may be greater than the spacing of letters on a visual acuity test, causing foveation of a letter other than the intended one. The ability to quickly know how many target letters are present may help the individual to localize the intended letter (Bedell et al., 2015).

In summary, the mechanisms which control crowded vision, or the ability to read letters in the presence of other visual information are strongly influenced by developmental factors which have varying rates of maturation, even into adolescence.

1.6 Crowding - History and Definitions

1.6.1 What is crowding?

Crowding is the reduction in ability to recognize objects in the midst of clutter and is present in everyday vision (Levi, 2008, Flom, 1991). Here, we shall look specifically at crowding in relation to letters or other target stimuli in the presence of distracting elements, or flankers.

In the 1930s, Ehlers described the difficulty of reading closely spaced letters compared with those in isolation (Ehlers, 1936), often ascribed as the first reference to what we now call ‘crowding’. Yet Strasburger and Wade argue that a Newtonian, James Jurin (1684-1750) could have been describing crowding when he wrote in 1738 that ‘the more complex an object, the more difficult it is to perceive its parts’ (Strasburger and Wade, 2015). In 1962, Stuart and Burian in their ‘Study of Separation Difficulty’, proposed that the crowding seen in strabismic amblyopes is an exaggeration of a normal physiological phenomenon (Stuart and Burian, 1962). The following year, Flom and colleagues published their classic experiment in which they quantified the reduction in near threshold resolution of a Landolt C when flanked by bars at varying distances (Flom et al., 1963b), see Figure 1.6.

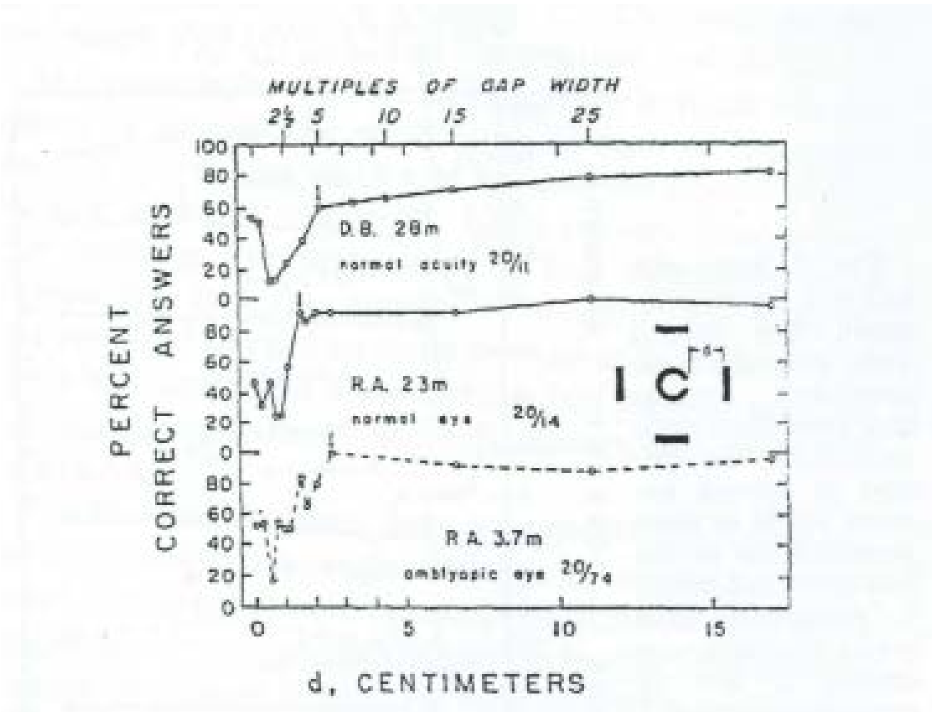


Figure 1.6, after (Flom et al., 1963b) Percentage of correct responses plotted against the linear separation of flanking bars for one normal eye and each eye of an amblyope.

Flom named this specific reduction in percent correct performance in the presence of flanking bars, 'contour interaction' and went on to distinguish between contour interaction and a wider definition of 'crowding' to include the effects of i) contour interaction, ii) attentional effects and iii) eye movements (Flom, 1991). In the literature, the terms 'crowding' and 'contour interaction' are often used interchangeably. In this thesis, the term 'contour interaction' is used to describe the specific reduction in visual acuity caused by the presence of nearby contours (Flom et al., 1963b); 'attentional effects' refers to the perceptual difficulty in discriminating the target from the flanking elements (Flom, 1991, Leat et al., 1999) and 'eye movements' includes both fixational instability and errors in saccades (Regan et al., 1992). The term 'crowding' is used here to describe the overall reduction in visual acuity which may result from a combination of contour interaction and deficits of attention and eye movements.

1.6.2 What are the properties that define crowding?

Crowding can be quantified by 2 parameters: its extent, the maximum distance from the target that nearby objects, or flankers, reduce the ability to recognise the target, and its magnitude, the loss in performance that results (Flom, 1991). Crowding is much stronger in peripheral than central (foveal) vision (Jacobs, 1979, Bouma, 1970) and the extent of the effect is broadly proportional to the eccentricity of the target (Bouma, 1970). The magnitude of the crowding effect depends on certain properties of the target and flanker - their spatial arrangement and orientation and also their similarity. There is stronger crowding in the adult periphery when flankers are from the same perceptual group, e.g. letters or pictures and are a similar size, colour and shape (Nazir, 1992, Strasburger et al., 1991, Kooi et al., 1994, Bernard and Chung, 2011, Reuther and Chakravarthi, 2014, Leat et al., 1999). Contour interaction in central (foveal) vision has a very small spatial extent, around 4 min of arc (Flom et al., 1963b, Siderov et al., 2013), with the maximum magnitude at a distance from the target of 0.4 letter widths, or 24 seconds of arc (Flom et al., 1963a).

1.7 Theories of crowding

1.7.1 Receptive fields

Dichoptic experiments have shown that contour interaction still occurs when target and flanker are presented to different eyes, placing the locus of interaction at least at the level of the striate cortex (Flom et al., 1963a, Kooi et al., 1994). A number of authors have supported theories of contour interaction which predict that resolution of a target is impaired if target and flanker fall within the same excitatory cortical annular receptive field (Flom et al., 1963b, Latham and Whitaker, 1996). Larger targets require larger receptive fields for their detection, but the finding that the extent of contour interaction changes little with increasing target size in peripheral vision, suggests that this mechanism alone does not fully explain the effect (Tripathy and Cavanagh, 2002). Recent support for a receptive field hypothesis was suggested by Bedell et al. (2013), who showed the magnitude of contour interaction to decrease under mesopic light conditions, consistent with the known reduction of antagonistic surround of cortical receptive fields in these conditions.

1.7.2 The physics of the stimulus

Hess et al. (2000) proposed an explanation for the contour interaction from bars surrounding a Landolt C, based on the physical properties of the stimulus. They suggested that when the bars came close to the C, the spatial frequency of the surrounded target increased, causing the visual system to use a scale of analysis that was less sensitive to gap detection in the target letter. This theory is not supported by the dichoptic experiments discussed earlier (Flom et al., 1963a).

Furthermore, the predictions of this theory have been found not to hold true for different sized targets and reversed polarity flankers (Hariharan et al., 2005, Liu, 2001) and for crowding by variously orientated Landolt Cs (Danilova and Bondarko, 2007) and the theory has been largely discounted as being the only explanation for foveal contour interaction.

1.7.3 Masking

Masking is the phenomenon whereby a pattern, or mask, overlaid on a target in space or time reduces its detectability or discrimination, although in cases of low contrast masks, discrimination can sometimes be enhanced (Levi et al., 2002b). Whilst crowding and masking share some properties, such as spatial frequency specificity (Chung et al., 2001, Legge and Foley, 1980), the effects of crowding in the periphery are much stronger than would be predicted by simple masking, so masking alone cannot account for crowding. In addition, the appearance of masked and crowded targets are not the same; in masking, the target disappears, whereas in crowding it becomes part of a jumbled percept (Pelli et al., 2004). It has been proposed that foveal crowding is distinct from that in the periphery and can be accounted for by a masking theory because of observations that the extent of crowding scales with stimulus size (Levi et al., 2002b, Song et al., 2014). However, different test paradigms have resulted in the opposite conclusion being drawn, that the extent of crowding in foveal vision has a fixed angular extent (Danilova and Bondarko, 2007, Siderov et al., 2013), giving weight to a dual mechanism of foveal crowding, with masking forming part of the explanation (Siderov et al., 2014).

1.7.4 Feature binding/pooling

As visual information moves to higher cortical areas, it is processed by receptive fields which are larger than those in V1. As the higher visual areas combine, or pool, information from lower areas, features become integrated and elements of target and flanker can become jumbled, or inappropriately ‘bound’ together (Parkes et al., 2001, Pelli et al., 2004, Greenwood et al., 2009). It is thought that the pooling of background features competes with the recognition of valid features (Nandy and Tjan, 2007). This explanation of crowding is supported by experiments such as that by Parkes et al. (2001), where observers were able to judge the average tilt of Gabor patches in peripheral vision, where tilt of individual patches was not able to be accurately discriminated. Thus, crowding can be thought of as part of the visual system’s tendency to ‘group’ similar features into a texture. Where flankers are ‘ungrouped’ from one another, by making them a different colour or shape, for example, crowding is reduced (Nazir, 1992, Kooi et al., 1994).

This model does not explain the greater crowding where flankers and target are from the same categorical group, despite similar features or the greater crowding caused by unfamiliar than familiar symbols (Reuther and Chakravarthi, 2014, Huckauf et al., 1999).

1.7.5 Attention models

Intriligator and Cavanagh (2001) adopted the term ‘attentional resolution’ to describe the smallest separation of two objects which allows them to be perceived as separate. They found this to be coarser than spatial resolution and suggested that crowding represented an attentional limit to visual resolution, a notion supported by others (He et al., 1996, Strasburger et al., 1991). Tripathy and Cavanagh went on to suggest that crowding was governed by attention receptive fields of a fixed size for each eccentricity (Tripathy and Cavanagh, 2002). Strasburger proposed a mechanism whereby top-down attentional control could over-ride bottom-up processing and that this theory could complement masking theories (Strasburger, 2005).

1.7.6 Two stage model

There is growing support for a two stage model of object recognition, where features are first detected, independent of each other and then integrated at a higher cortical level to allow object recognition to occur (Levi, 2008, Pelli et al., 2004, Chung et al., 2001, Parkes et al., 2001). Crowding could then occur at multiple levels of the visual system, depending on the nature of the object and flankers (Whitney and Levi, 2011, Manassi et al., 2013, Anderson et al., 2012). This model does not necessarily exclude the limited attentional resolution theory and could be an alternative description of the same mechanism (Hariharan et al., 2005).

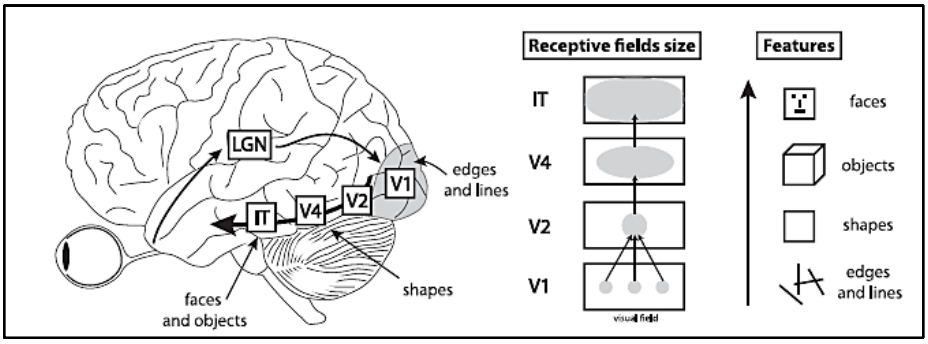


Figure 1.7 after Manassi et al. (2013), showing the hierarchy of visual processing, whereby simple contours like lines and edges are processed in V1 and more complex features are processed in higher visual areas, with larger receptive fields.

1.7.7 Recent grouping theory

Certain findings such as the reduction in crowding which occurs when flankers group together are difficult to explain with the theories above and have led Herzog and colleagues to propose a model which contradicts the hierarchical model of visual processing. They suggest that grouping is paramount and that high and low level processing interact with crowding determined at the final stage, along with overall appearance (Herzog et al., 2015).

1.8 Crowding in children

If maturation of crowded acuity is slower than that of single letter acuity, as discussed in section 1.4.1, what is known about the relative maturation of the various contributors to the overall crowding effect: the influence of contour interaction, the effect attentional factors and eye movements?

1.8.1 Extent and magnitude of contour interaction

There is evidence from several studies (Matsumoto et al., 1999, Semenov et al., 2000, Jeon et al., 2010) that the critical spacing for foveal contour interaction is up to twice as large in children as in adults. The age at which the critical spacing reaches adult levels was found by Semenov et al. (2000) to be 9 years for Landolt C targets and by Bondarko and Semenov (2005) to be around 12 years of age for Landolt C and E targets, whereas Jeon et al. (2010) found that at age 11, the critical spacing was still greater than in adults for E targets (Figure 1.8). Differences in experimental methods and targets used have led to these different conclusions being drawn about when the extent of contour interaction is adult-like.

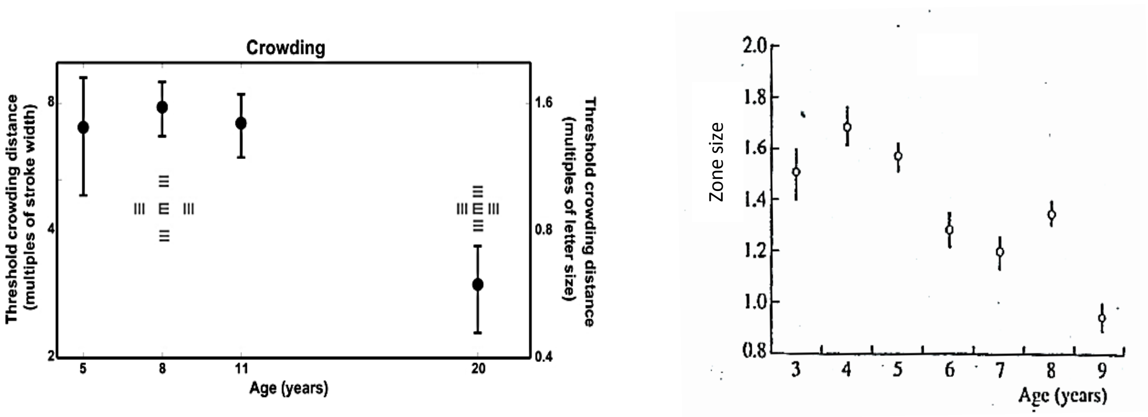


Figure 1.8 Left panel after Jeon et al. (2010) and right panel after Semenov et al. (2000) showing extent of crowding against age. E targets with sets of 3 flanking bars were used in the study by Jeon et al. (2010) and contour interaction was found to be not adult-like at 11 years of age. In the study by Semenov et al. (2000), C targets with tangential flanking bars were used and contour interaction was judged to be adult-like at 9 years.

It is uncertain if the magnitude of contour interaction in children is different to adults. Manny et al. (1987) investigated contour interaction in foveal vision using a Landolt C target with tangential bars. They concluded that there was no significant difference in the magnitude or extent of contour interaction between adults and children aged 3 and 4, although data from only 12 children were included and individual variations were noted. Atkinson and Braddick (1982) drew a different conclusion regarding the magnitude of contour interaction. They used a Landolt C target surrounded by a circular array of Cs and Os at a fixed inter-optotype spacing to compare 'crowded' with single optotype acuity. In normal 5 year olds, the resultant 'crowded' acuity, with a fixed level of contour interaction, was found to be only 58% that of adults. Furthermore, Atkinson et al. (1988) used a target letter surrounded by four other letters, again at a fixed inter-letter spacing and found the ratio between the surrounded letters and the single letters in 5-7 year olds was similar to adults, but significantly greater in 3-4 year olds. In a recent study, Doron et al. (2015) showed a reduction in the magnitude of crowding up until the age of 6-7 years, after which adult-like levels were reached. Variation in targets and flanking elements could contribute to the different results in these studies, as differently sized and shaped targets may not be processed by the same cortical receptive fields.

1.8.2 Effect of attention

In adult foveal vision, the main variable which affects crowding is the proximity of the flanking elements (Atkinson, 1991), or contour interaction; the structural similarity of target and flanker has been found not to matter (Leat et al., 1999).

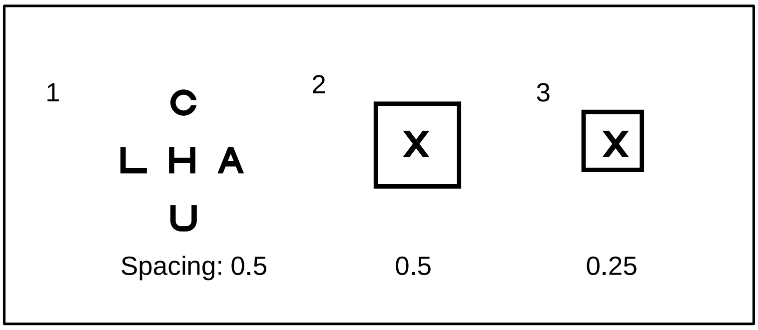


Figure 1.9, after Atkinson (1991). In adults, poorest vision was in format 3, a box surround at 0.25 letter widths from the target, whereas in children, poorest vision was in format 1, letter flankers at 0.5 letter-widths from the target.

There is some evidence, however, that in children's foveal vision, target-flanker similarity does reduce a child's ability to recognize a target letter. In a study by Atkinson (1991), in adults, worse vision resulted from format 3 (Figure 1.9), a box surround at 0.25 letter widths from the target, whereas in children, worst vision was in format 1, letter flankers at 0.5 letter-widths from the target. In children, the letters seem to crowd the target more than a box, because the task of separating the target letter from flanking letters adds a level of difficulty not experienced by the adults. This influence of target-flanker similarity could reflect the development of visual attention; the ability to select the target from the non-target information in the visual field is made easier when the target is dissimilar to the surrounding features (Desimone and Duncan, 1995). Atkinson's study suggests an effect of attention on the magnitude of the crowding effect, which warrants further investigation as support for such an effect in the literature is sparse.

A recent study using a visual search paradigm showed an influence of target-distractor similarity on visual search in children aged 4-8, with children making more fixations when target-distractor similarity is high (Huurneman and Boonstra, 2015).

1.8.3 Effect of eye movements

Immature development of eye movement control may also contribute to foveal crowding in children. Kothe and Regan (1990) found reduced Snellen acuity in some young children who had good acuity in a repeat letter chart (Figure1.10). They attributed this to a delayed control of gaze selection, a notion supported from direct measurement of children's fixational eye movements. An increase in the variability of fixational eye movements in young children has been reported (Figure 1.11) (Aring et al., 2007, Kowler and Martins, 1982) but it is not clear whether, or to what extent such fixational instability is sufficient to interfere with visual acuity (Flom, 1991, Aslin and Ciuffreda, 1983). Recently, Bedell and colleagues have argued for an eye-movement contribution to foveal crowding based on poorer identification of long compared to short letter strings (Bedell et al., 2015).

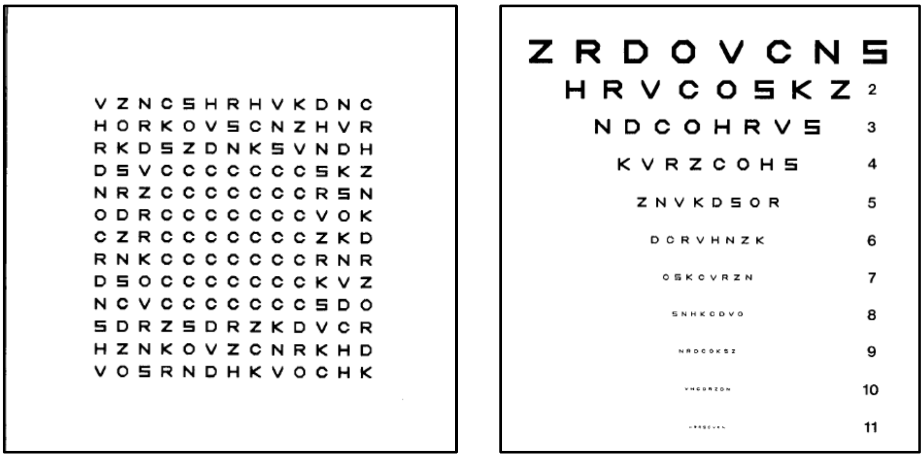


Figure 1.10 The repeat letter and Snellen charts used by Kothe and Regan (1990).

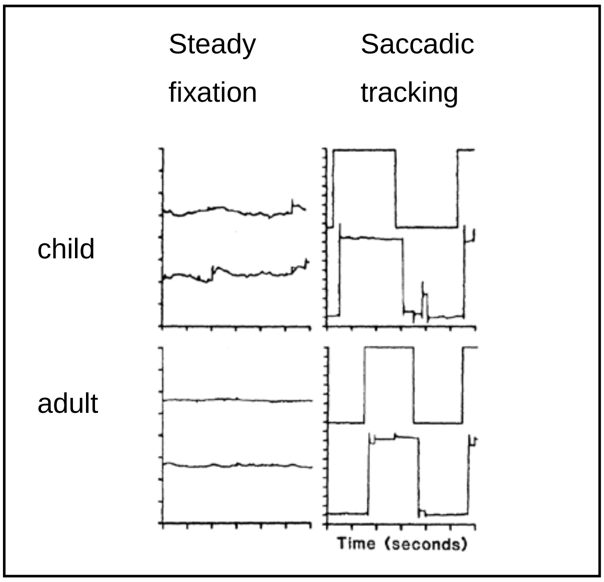


Figure 1.11, after Kowler and Martins (1982), showing eye movement recordings from a 5 year old child and an adult, during steady fixation and saccadic tracking. Top traces show horizontal movements and bottom traces, vertical movements.

Whilst there has been a significant amount of research into crowding in recent years, much of it has concentrated on trying to ascertain what crowding is, its properties and likely mechanisms. As the effect is more evident in peripheral vision, most studies have focused on the adult periphery. Levi's review of crowding highlights the need for more research into the development of crowding (Levi, 2008) and Leat's review points out that the age at which children's vision becomes adult-like is not fully known (Leat et al., 2009).

1.9 Amblyopia

1.9.1. Definitions and prevalence

Amblyopia is a developmental syndrome, whereby neuroplasticity at birth drives structural and functional changes. It is characterized by deficits in visual acuity, contrast sensitivity, spatial localization, fixation, ocular motility, accommodation, crowding, attention, motion perception and temporal processing (Asper et al., 2000). Traditionally, it has been thought to be caused by interruption to visual input because of strabismus, anisometropia, high refractive error or form deprivation (McKee et al., 1992) and it is on the basis of these associations that amblyopia is classified, the most common types being strabismic and anisometropic amblyopia. However, there is now some evidence that anisometropia and strabismus may also arise as an effect of amblyopia, rather than the primary cause (Barrett et al., 2004, Barrett et al., 2013). Differences in the structure and function of the visual systems of strabismic and anisometropic amblyopes have been described, suggesting different neural mechanisms (Hess et al., 1983).

The prevalence of amblyopia in the UK, defined as visual acuity of worse than 0.2 logMAR or an inter-ocular difference of 0.2 logMAR, in the absence of ocular pathology, is around 3.6% (Williams et al., 2008). Other recent studies have estimated prevalence in the US to be 2.5% (Arnold, 2013) or 7.7% (Pascual et al., 2014) and 1.9% in Australia (Pai et al., 2012). Variations in the data can be accounted for in the lack of a standardized definition of amblyopia, by ethnic differences and access to screening and treatment. For review see Solebo et al. (2014). The prevalence of amblyogenic risk factors (e.g. strabismus, anisometropia, hypermetropia) is estimated around 21%, although not all individuals with the risk factors go on to develop amblyopia (Arnold, 2013).

1.9.2 Implications of amblyopia

The implications to quality of life of amblyopia and its risk factors and treatment have been described in the literature; for review see Carlton and Kaltenthaler (2011) and Grant and Moseley (2011). It is often difficult to differentiate the effects of amblyopia from those related to treatment and strabismus. In addition, in studies parents are often asked about impact on children, which may not be a true reflection on what the children themselves believe and experience. Factors which have been reported to be caused (at least in part) by amblyopia are - anxiety, negative interactions with peers, impact on activities and education, self-esteem and self-image (Carlton and Kaltenthaler, 2011).

In a population-based questionnaire study, Wen et al. (2011) found no differences in General Health Related Quality of Life (GHRQoL) in pre-schoolers with amblyopia to those without, but found GHRQoL to be significantly worse in pre-schoolers with strabismus. One of the studies to question the children themselves about self-perception of social acceptance was that of Webber et al. (2008). Children aged 9 with history of patching had lower scores than age matched controls, but no difference was found between those with a history of strabismus or spectacle wear and normals. In addition, significant differences in subjective and psychological functions have been found between amblyopic and non-amblyopic teenagers (Sabri et al., 2006).

In addition to quality of life issues, other potential difficulties which amblyopes may face are occupational vision requirements and implications of injury to the fellow eye. There are a number of occupations in the UK where a minimum vision requirement in the poorer eye is specified (Carlton and Kaltenthaler, 2011), thus excluding some people with untreated or residual amblyopia that persists into adulthood due to poor response to or compliance with treatment. Perhaps the strongest reason for screening for and treating amblyopia is the risk of vision loss in the non-amblyopic eye. A study in the UK determined the lifetime risk of impairment to or loss of vision in the fellow eye to be 1.2% (Rahi et al., 2002), whilst a Finnish study reported a risk of vision loss in the fellow eye to be 0.175%, which is significantly higher than the rest of the population (Tommila and Tarkkanen, 1981).

1.9.2. Neural plasticity and critical periods

Pioneering work by Hubel and Wiesel showed the effect of monocular deprivation on the ocular dominance of cells in the primary visual cortex of first cats then monkeys (Hubel et al., 1977, Wiesel and Hubel, 1963). They described a critical period as the time during which deprivation can cause change. Plasticity refers to the ability of the brain to reorganize its connections in response to environmental stimuli; high levels of plasticity are present at birth and decline during the critical period (Wong, 2012). If the amblyogenic factors of strabismus, anisometropia or deprivation occur in adult humans, amblyopia does not result (Kiorpes, 2002). It is now thought that there are 3 sub periods - the period of normal development, the period during which amblyopia can occur and the period during which treatment can be effective (Daw, 1998, Lewis and Maurer, 2005). The period of time during which amblyopia can occur in humans is a matter for some debate, and is different for different visual functions, higher levels of the visual system having longer critical periods. It is generally thought to include the first 8 years of life, although the period of time during which improvements can be made to visual function continues beyond 8 years, into teenage years and even adulthood (Daw, 1998, Pediatric Eye Disease Investigator Group, 2004, Pediatric Eye Disease Investigator Group, 2005).

The implications for clinicians are that treatment is more effective when commenced early in the critical period and that visual functions with a shorter critical period should be treated first (Daw, 1998). This does not reflect the traditional approach to amblyopia treatment, but supports the view that after surgical correction of strabismus and improvement to visual acuity, a full rehabilitation programme could include treatments to improve stereoacuity (Xi et al., 2014), Vernier acuity (Snell et al., 2015), contrast sensitivity (Li et al., 2015) and reading speed (Chung, 2011).

1.9.3 Visual deficits in amblyopia

Psychophysical experiments show several distinctions between visual function in anisometropic, strabismic and mixed strabismic/anisometropic amblyopia. Contrast sensitivity is affected across the entire visual field in anisometropic amblyopia, whereas losses are confined to the central field in strabismic and mixed strabismic/anisometropic amblyopia (Gstalder and Green, 1971, Hess and Howell, 1977). Furthermore, strabismic amblyopes show positional uncertainty, not shown in anisometropic amblyopia (Levi et al., 1987, Hess and Holliday, 1992). In Vernier acuity and bisection acuity tasks (both cortical functions) performance of anisometropic amblyopes resembles blurred normal vision i.e. it scales with grating acuity, whereas performance of strabismic amblyopes resembles the normal periphery – it is disproportionately reduced compared with grating acuity (Levi and Klein, 1985, Levi et al., 1987). These findings infer either a reduction in cortical sampling because of a loss of binocular neurones (Levi et al., 1987), scrambled connections between cortical cells (Hess et al., 1999) or some other sort of anomalous mapping (Sireteanu and Fronius, 1989, Lagreze and Sireteanu, 1991). Using contour integration experiments, Hess and colleagues proposed that positional uncertainty can be explained by the relative difference in the cortical maps formed by the two eyes and not solely by anomalous connections in the amblyopic eye (Hess et al., 1997) and Kiorpes and McKee (1999) have suggested that topographic disarray exists at a higher level. Barrett et al. (2003) have proposed a model whereby reduced neural representation in the primary visual cortex of the amblyopic eye results in a percept which resembles a combination of two differently-orientated gratings. This model is supported by a close resemblance to reported misperceptions by amblyopic participants.

Deficits at higher levels of the visual systems of amblyopes have been reported, such as perception of entire scenes (Mirabella et al., 2011), number processing

(Mohr et al., 2010), and tasks involving higher order attention (Sharma et al., 2000, Ho et al., 2006).

It is likely that a combination of neural undersampling and abnormal connection models may explain the experimental data, or a more complex theory involving abnormal temporal processing and difficulty in directing attention to information from the amblyopic eye (Asper et al., 1999).

1.9.4 Oculomotor deficits in amblyopia

The loss of, or reduction in binocularity in amblyopia causes impairment of tasks such as hand-eye co-ordination, reaching, grasping and driving (Grant and Moseley, 2011, Niechwiej-Szwedo et al., 2011). Of relevance here are the potential eye movement and reading deficits as they relate to visual acuity measurement.

Disruption of fusion during development gives rise to gaze instability; unsteady fixation in adult amblyopes has been characterized by a slow nasal drift with saccadic intrusions, or microsaccades (Schor and Hallmark, 1978, Schor, 1975, Ciuffreda et al., 1991, Zhang et al., 2008), although given the instruction to hold gaze steady, there is evidence that intrusive saccades can be controlled (González et al., 2012). The drift movements could move the image to an extra-foveal location resulting in poorer or variable visual acuity (Flom, 1991) and microsaccades have the potential to reduce vision through position variability (Chung and Bedell, 1995).

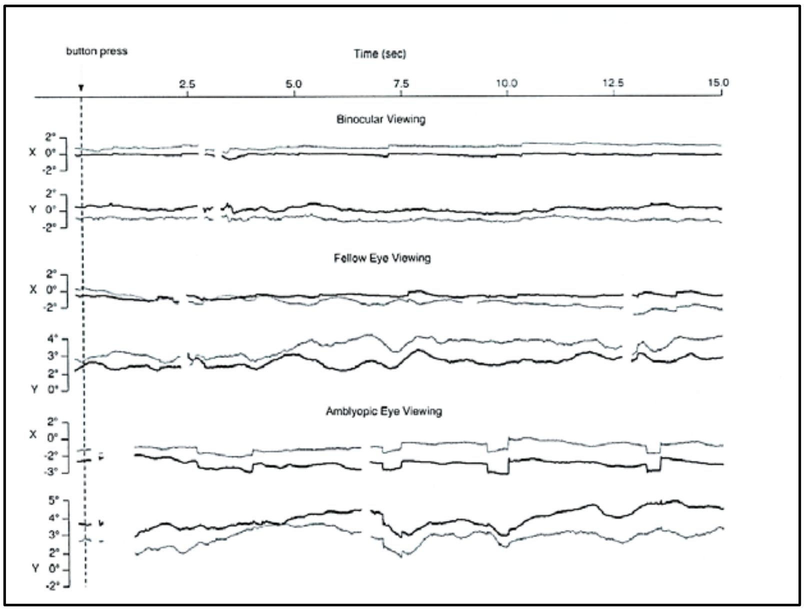


Figure 1.12 after González et al. (2012). Horizontal (X) and vertical (Y) eye movement recordings from an adult strabismic amblyope given the instruction to look straight ahead at a fixation target. The amblyopic eye was occluded for viewing with the fellow eye and the fellow eye was occluded for viewing with the amblyopic eye. Black lines represent the fellow eye and grey lines the amblyopic eye. Poor fixation stability is demonstrated by the amblyopic eye.

Whether fixational instability can cause a reduction in acuity is a matter for debate; Subramanian et al. (2013) and Chung et al. (2015) have found a correlation between fixational stability and visual acuity, not found by González et al. (2012). Nevertheless, the existence of a correlation does not tell us whether poor fixation causes reduced acuity or vice versa.

Abnormalities have also been reported in saccadic and smooth pursuit movements of amblyopes. Strabismic amblyopes make more saccades in reading (Kanonidou et al., 2010) and can show inaccurate and asymmetric smooth pursuit movements (Bedell et al., 1990). In anisometropic amblyopes, latency of saccades is longer and saccades are less accurate (Niechwiej-Szwedo et al., 2010).

Fixation instability has also been reported in amblyopic children (Carpineto et al., 2006, Subramanian et al., 2013, Birch et al., 2013) and found to be greater than that in amblyopic adults (Subramanian et al., 2013). It often presents as fusion maldevelopment nystagmus syndrome (FMNS), characterized by slow nasal drifts followed by temporal corrective 'flicks' (Tychsen et al., 2010). Abnormal fixation is thought to arise as a consequence of decorrelation of input from the two eyes, central suppression and poor visual acuity. Where there is decorrelation only, in the case of strabismus without amblyopia, fixation instability is noted, but is less than when amblyopia is also present (Subramanian et al., 2013). Birch and colleagues noted a strong correlation of fixation instability with poor stereopsis (Birch et al., 2013).

1.9.5 Treatment of amblyopia

Traditionally, amblyopia has been treated with the concurrent use of spectacles and occlusion therapy with patching or pharmacological penalization (Moseley, 2002). Penalization or patching of the fellow eye degrades or removes its image, forcing use of the amblyopic eye (Taylor et al., 2012, Birch, 2013). Following the publication of two large studies, the Monitored Occlusion of Treatment of Amblyopia Study (MOTAS) (Stewart et al., 2004) and the Amblyopia Treatment Studies carried out by the Paediatric Disease Investigator Group (PEDIG) (Repka and Holmes, 2012, Pediatric Eye Disease Investigator Group, 2005, Pediatric Eye Disease Investigator Group, 2004), there has been a general move to part-time rather than full-time patching (Fresina and Campos, 2014). Furthermore, there is evidence that significant improvements in visual acuity can be made in some cases with spectacle wear alone (Cotter et al., 2007, Steele et al., 2006, Moseley et al., 2002, Chen et al., 2007). Recent Cochrane reviews conclude that for strabismic amblyopia, occlusion and refractive correction provide a better outcome that refractive correction alone

(Taylor and Elliott, 2014) and in refractive amblyopia, occlusion can help if reduced acuity persists after spectacle correction alone (Taylor et al., 2012).

Problems with patching include variable compliance (Simonsz et al., 1999, Loudon et al., 2002) and loss of self-esteem (Webber and Wood, 2005) and use of atropine sulphate for penalization can cause allergic, toxic and systemic effects (Tejedor and Ogallar, 2008). Furthermore, regression of visual acuity after cessation of patching and/or pharmacological penalization can occur (Mohan et al., 2004, Rutstein and Fuhr, 1992, Kaye et al., 2002, Pediatric Eye Disease Investigator Group, 2007) and both patching and penalization interfere with binocularity (McKee et al., 2003, Holmes and Clarke, 2006). Birch found correspondence in the risk factors for poor stereoacuity and persistent amblyopia and concluded that insufficient attention to binocularity during treatment contributes to incomplete treatment success, gaze instabilities and recurrent acuity decline (Birch, 2013).

Recent advances in amblyopia treatment have seen improvements in the less plastic visual systems of amblyopic older children or adults through perceptual learning. Perceptual learning involves practising a challenging task to gain improvements in performance and in the context of amblyopia therapy, the gains in performance should be transferrable to improvements in visual acuity (Birch, 2013, Levi and Li, 2009). Tasks which have shown improvements include contrast detection (Polat et al., 2004, Chen et al., 2008, Huang et al., 2009), position discrimination (Li et al., 2008) and Vernier acuity (Levi et al., 1997). Results could be attributed to better control of eye movement or accommodation or to harnessing higher level attention to improve cortical efficiency at reducing noise (Levi and Li, 2009). Further improvements to techniques have led to the use of video games to improve compliance and attentional stimulation (Li et al., 2011, Jeon et al., 2012, To et al., 2011).

In many cases, perceptual learning is carried out in conjunction with patching, which does not address the suggestion that treating amblyopia should first tackle suppression (Hess et al., 2010b). Consequently, Hess and colleagues have developed a dichoptic system which presents images of different contrasts to the 2 eyes (Hess et al., 2010a). The relative contrast between the 2 eyes is changed as the amblyopic eye improves and after a few weeks of daily 1 hour practice, improvements in VA were recorded in a few strabismic adults. Other researchers have found gains to stereovision in children and adults with perceptual learning (Knox et al., 2012, Xi et al., 2014), a finding which gives hope for avoiding persistent amblyopia (Birch, 2013).

In summary, there is evidence that new forms of treatment can bring improvements even beyond the critical period of development and can also improve stereopsis, which offers better long-term visual function for people with amblyopia (Levi et al., 2015). Nevertheless, young children remain most amenable to improvement through treatment, so identifying amblyopia in young children remains a priority (Kulp et al., 2014).

1.9.6 Crowding in amblyopia

Foveal crowding has been found to be greater in extent in amblyopic eyes than in normal eyes and has been likened to crowding in the normal periphery (Flom, 1991, Levi and Klein, 1985). Is this increased crowding as result of greater contour interaction, poorer control of eye movements, or attention deficits? This question is addressed in research questions 7 and 8.

Some authors have reported that when scaled to individual resolution threshold, contour interaction was similar for amblyopic and normal eyes (Simmers et al., 1999, Flom et al., 1963b), yet others have reported that in amblyopic vision, the extent of crowding is greater than even the reduced acuity would predict (Hess et al., 2001, Levi et al., 2002a, Hariharan et al., 2005). Several studies, in children (Greenwood et al., 2012) and in adults (Bonneh et al., 2004), found both features, where excessive contour interaction was found in the strabismic and mixed strabismic/anisometropic groups but not in the anisometropic group. Possible mechanisms for increased contour interaction in amblyopia include abnormal lateral interactions (Polat et al., 1997), excessive feature integration (Levi et al., 2002a) or extended pooling (Hariharan et al., 2005).

Regan and colleagues proposed a theory for the excessive crowding seen in some amblyopes based on defective selection or control of gaze (Regan et al., 1992). They compared Snellen acuity with that from repeat letter charts in amblyopic children and adults and found a proportion whose repeat letter acuity was significantly better than their Snellen acuity, despite greater contour interaction in the repeat letter chart. This they attributed to poor control of gaze or inaccurate fixation.

Kanonidou and colleagues measured reading speed and tracked eye movements of strabismic amblyopic and normal observers and found that strabismic amblyopes made more saccades per line than controls (Kanonidou et al., 2010). In contrast to the conclusions of Levi et al. (2007) that reduced reading speeds in amblyopes can be explained fully by crowding effects (contour interaction), Kanonidou concluded that slower reading speeds of amblyopes could not be accounted for solely by spacing. The study by Levi et al used Rapid Serial Visual Presentation (RSVP) to eliminate the effect of eye movements, so it could be that oculomotor deficits add a hindrance to amblyopic reading in addition to contour interaction.

As discussed earlier, (section 1.7.5), attentional theories of crowding suggest that features are detected but there is not enough attentional resolution to resolve them. Deficits in visual attention have been proposed in people with amblyopia and fMRI studies have shown high level cortical processing abnormalities in strabismic amblyopes compared to controls (Secen et al., 2011). Popple and Levi (2008) showed an altered time course of attention in amblyopic eyes in the 'attentional blink' paradigm, where to targets are presented in rapid succession; Ho et al. (2006) used a tracking task to show attentional deficits in both strabismic and anisometropic children and Sharma et al. (2000) showed deficits in counting elements by strabismic amblyopes, thought to be a higher level limitation in the ability to individuate objects. In measuring visual acuity, we are more concerned with the spatial than the temporal domain, which forms the basis of some of these studies. Nevertheless, in a complex visual acuity chart, the ability to select and name a target letter from the midst of other letters, then identify and move to the next letter and so on could be impaired in an individual with deficient visual attention.

1.10 Research Questions

There is much about foveal crowding which is not well understood and it is likely that it is not governed by a single mechanism. Visual acuity tests where optotypes are used as flanking elements are likely to deploy different mechanisms than those that use simple bars, and tasks that involve reading a line of letters require eye movements other than the steady fixation required to look at an isolated letter. Crowded acuity tests with different features have been judged to be equivalent to each other because they give a similar result, even though the crowding may arise from different combinations of contour interaction, eye movements and attention, e.g. Stager et al. (1990). The danger here is that they may not give an equivalent result in groups with abnormal crowding, e.g. young children or amblyopes (Flom, 1991).

The purpose of my experiments is therefore to disentangle and broaden our understanding of the contributions of contour interaction, eye movements and attention to foveal crowding in developing children and people with amblyopia.

The first study in this thesis, described in Chapter 2, used 3 crowded logMAR charts, each in common use in the UK, to measure vision in a population of school children aged 4-9. The research questions are:

1. What is the effect of chart design on measured acuity in children aged 4-9?
2. What is the effect of age on crowded acuity?

Chapter 3 describes the development of custom-designed tests, which allow the crowding features in the tests to be controlled and manipulated to establish their relative effects. These tests are used in a study, described in Chapter 4, to compare crowding in children of different ages, with adult controls. The effect of target-flanker similarity was explored by comparison of threshold logMAR for recognition of a letter or line of letters with either bar or letter flankers. The effect of eye movement control was explored through comparison of threshold logMAR in single letter and linear letter recognition. In addition, an analysis of errors compared mis-named letters in the linear charts. Adjacent errors occurred when the named letter was immediately adjacent to the target letter. Other errors were defined as random errors. Poor eye movement control was predicted to cause a higher proportion of adjacent errors. Errors were compared across the age groups and in the two linear flanking conditions- letter and line flankers.

In addition, information from the youngest group and the adults was pooled for two of the crowded charts (showing the least and the most crowding) and the psychometric functions were derived, as described in Chapter 5. Comparison of the slopes of the psychometric functions enabled predictions to be made regarding the effect of crowding on the repeatability of the tests.

The research questions are:

3. What is the effect of spacing between a flanking bar and target letter on acuity in children and adults?
4. What are the relative contributions of contour interaction, gaze control and attention to crowded acuity in children and adults?
5. Can mis-naming errors point to any differences between reading behaviour of line charts in children and adults?
6. What is the effect of crowding on the slopes of psychometric functions derived from acuity charts in adults and children?

In the final study, described in Chapter 6, the effect of crowding on amblyopic adult vision was explored. Using similar charts to the second experiment enabled comparison with the normal, developing fovea.

The research questions are:

7. What are the relative contributions of contour interaction, gaze control and attention to crowded acuity in adults with strabismic or mixed strabismic/anisometropic amblyopia?
8. Can mis-naming errors point to any differences between reading behaviour of crowded visual acuity tests in the amblyopic and fellow eyes of participants with strabismic or mixed strabismic/anisometropic amblyopia?

Chapter 2

Crowding in children's visual acuity tests - effect of test design and age

2.1 Purpose

As discussed in Chapter 1, section 1.4.3, visual acuity measurement in young children was traditionally made easier by using single optotypes (letter or picture) (Keith et al., 1972); however, such tests were found to over-estimate visual acuity as they do not take account of the crowding phenomenon (Youngson, 1975, Hilton and Stanley, 1972, Flom et al., 1963b, Manny et al., 1987). Use of picture optotypes can also improve testability in young children, but issues with variable legibility, complexity of shape and empirical sizing can reduce comparability with adult charts (Fern and Manny, 1986, Friendly, 1978, Little et al., 2012, Candy et al., 2011, Simons, 1983).

In order to avoid the over-estimation of acuity which arises from single optotype tests and to make acuity tests more sensitive to amblyopia detection, children's visual acuity tests have been designed to induce crowding. A number of such tests have been produced using letter or picture/symbol optotypes. However, the overall level of crowding may differ between tests because of the lack of standardisation of the individual components of crowding. For example, surrounding a single letter with flanking bars close to the optotype induces contour interaction, thereby impairing recognition, but may not require the same level of gaze control accuracy required to read a series of letters along a line. Also the separation of optotypes from each other and from the surround bar is not standard, and could result in variable levels of contour interaction. The ETDRS Test uses a separation of 1.0 letter width (Early Treatment Diabetic Retinopathy Study Group, 1985), which has also been used in the Sonksen Test, but the LogMAR Crowded Test uses a separation of 0.5 letter widths. In the Sonksen test the distance between the letters and the box surround below and to the sides is the width of the optotypes in the display being shown whilst the distance to the box at the top is the width of a letter in the preceding larger display.

The purpose of this study was to look for an effect on visual acuity resulting from the variation in design of commercially available acuity tests in children of different ages and to answer the following:

1. What is the effect of chart design on measured acuity in children aged 4-9?
   - using different inter-optotype and optotype-flanker separations
   - using a picture optotype test rather than a letter optotype test
2. What is the effect of age on crowded acuity in children?

Visual acuity was measured in a sample of primary school children using the following tests: the logMAR Crowded Test (Keeler Ltd, Windsor, UK), the Sonksen logMAR Test (Haag-Streit, Harlow, UK), the Kay Picture Crowded logMAR (Kay Pictures Ltd, Tring, UK) and the Kay Picture Single logMAR Tests (Kay Pictures Ltd, Tring, UK) and the Revised Sheridan Gardiner Test (Keeler Ltd, Windsor, UK). These tests were chosen as they are in common use in the UK (Wickham et al., 2002) and contain a range of features: the two letter tests with linear presentation have different letter-flanker separations and the Kay Pictures test has larger, empirically sized optotypes. Single letter and picture tests were included with which to normalize the results from the crowded tests. Our results showed that there is an age effect of crowding, based on separation of optotypes and type of optotype used (letter or picture).

2.2 Methods

2.2.1 Participants

School children, aged 4-9, were recruited from a primary school in Cambridgeshire, UK. For analysis, the children were considered in two groups. Children in the younger group (39 participants) were aged between 4 years 10 months and 6 years 9 months, mean 5 years 9 months. Children in the older group (64 participants) were aged between 7 years 9 months and 9 years 8 months, mean 8 years 7 months. The number of participants in each group was sufficient to obtain a power of 80% at the 5% level (two-tailed) for an effect size of 0.1 logMAR. An equal number of children in each age group were invited to participate in the study, but a greater number from the older group responded and for reasons of equity, were included. Although the number of children in each group were not equal, the age range represented in each group were approximately equal, i.e. around 2 years. Children's development is a continuous process and one approach would have been to treat age as a continuous variable, rather than to group the children into age bands. In looking at the relative development of crowded and uncrowded acuity, age was used as a continuous variable, but I was also interested in whether there was a significant difference in crowding between the tests in the youngest children, in primary level 'Key Stage 1', who were learning to read and those more practised readers in 'Key Stage 2'. It was originally decided to sample a third group of children aged 10-12, but initial results showed that the 7-9 year group showed similar results to the adult controls, so it was decided that there would be little additional information gained from testing a third group.

Written informed consent from the children's parents or guardians and verbal assent from the children was obtained before any data were collected. All children with a completed consent form who were available on the day of testing participated, the only exclusions from the results were children unable to co-operate with the testing protocol (3 did not comply). Approval of the study protocol was given by our Institutional Research Ethics Committee and the study followed the tenets of the Helsinki Declaration.

Table 2.1 Summary of the features of the 5 children's acuity tests used in the study.

	logMAR Crowded LMC	**Sonksen S**	**Sheridan Gardiner SG**	**Crowded Kay CK**	**Single Kay SK**
Optotypes used	X V O H U Y	X V O H U T	X V O H U T A	8 Kay pictures	8 Kay pictures
optotypes/row	4	4	1	4	1
inter-optotype spacing (optotype widths)	0.5	1.0	none	0.5	none
optotype-box spacing (optotype widths)	0.5	Above - 1.0x the next larger optotype size. Below and sides 1.0	none	0.5	none
testing distance used in study	3m	3m	6m	6m	6m
range of acuities (logMAR)	0.8 to -0.3	0.8 to -0.3	1.0 to -0.3 (Snellen 6/60-6/3)	0.7 to -0.4	0.7 to -0.3
size progression	0.1 logMAR	0.1 logMAR	traditional Snellen progression	0.1 logMAR	0.1 logMAR

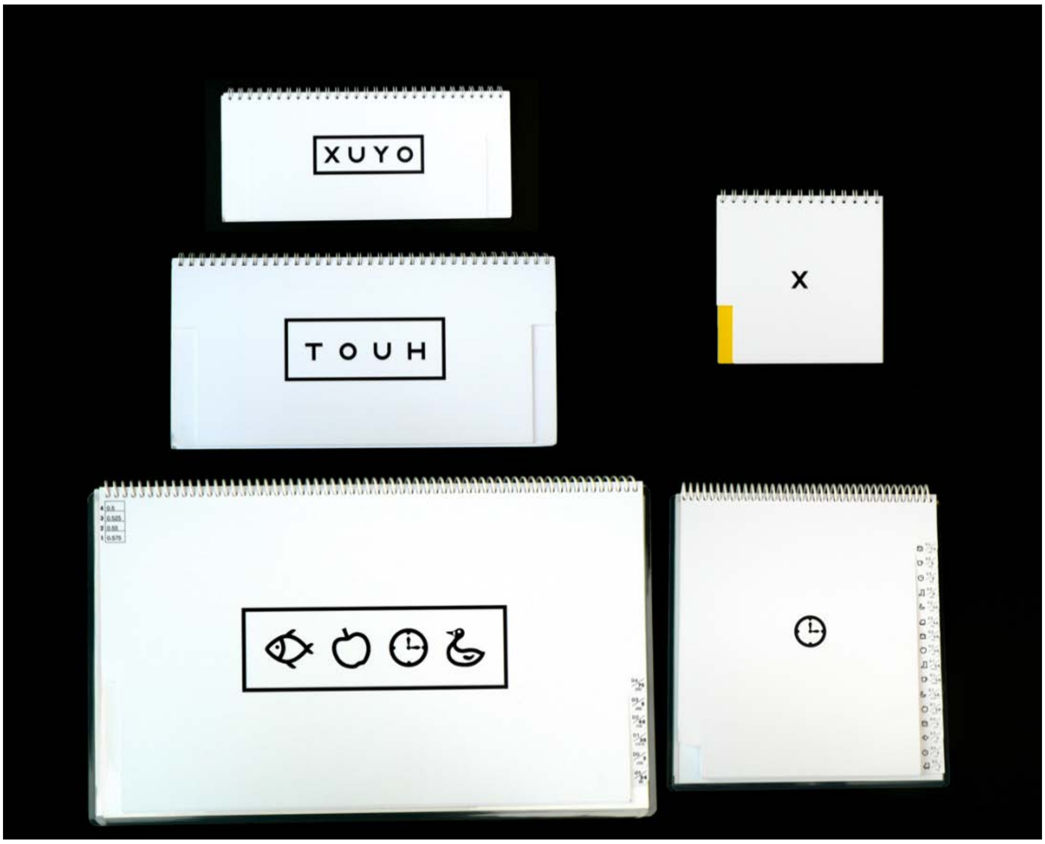


Figure 2.1. The five tests used in the study. The left column from top to bottom shows the logMAR Crowded Test, the Sonksen logMAR Test and the Crowded Kay Picture Test. The Sheridan Gardiner Test is shown in the top part of the right column and the Single Kay Picture Test below.

2.2.2 Visual Acuity Tests: design and scoring

The tests used in the study are depicted in Figure 2.1 and a summary of their main features is shown in Table 2.1. Each of the 3 crowded tests comes in flip-book form with 4 optotypes presented horizontally on each page enclosed in a surrounding box. The 2 single optotype tests are also in flip books with 1 optotype per page and no surrounding box. To facilitate comparisons between the tests, the following modifications to the recommended testing protocols were introduced:

- Scores for the Sheridan Gardiner Test were converted to the nearest logMAR and letter-by-letter scoring was used.

- The orthoptic version of the Sheridan Gardiner test was used as this measures acuity to 6/3, whereas the highest acuity able to be measured with the standard version is 6/6.
- Where only 3 different optotypes of a given size were available in the single optotype tests, the first optotype was shown a second time. Thus, for every test, children were presented with 4 optotypes of any one size.
- To score the crowded logMAR test in a clinical setting a modified logMAR scale is recommended by the manufacturers, where the score is 1 - the log of the minimum angle of resolution, such that 6/6 has a score of 1 and 6/60, a score of 0. For the purposes of our study, we used conventional logMAR scoring, where 6/6 has a score of 0 and acuities better than 6/6 are negative.
- Both Kay Picture Tests are designed for use at a 3m test distance, but a floor effect was possible as the smallest optotype size is logMAR -0.1 in the crowded test and 0.0 in the single optotype test. Accordingly, the test distance was increased to 6m and the visual acuity scores modified accordingly, allowing logMAR to -0.4 and -0.3 to be measured, respectively. Thus, the LogMAR Crowded and the Sonksen Tests were viewed directly at a 3m test distance and the Sheridan Gardiner and the 2 Kay Pictures Tests were viewed at a 6m test distance through a front-surface optical quality mirror.

Figure 2.2 Experimental set-up for direct viewing of the 3m tests.

2.2.3 Protocol

Testing took place in the children's school hall under illumination adequate for visual acuity testing, approximately 100 lux (National Academy of Sciences-National Research Council Committee on Vision, 1980). Before testing, the children were familiarized with the Kay Picture optotypes and matching cards were given to the 4 and 5 year old children showing the Kay pictures and letters used in the tests; these were retained by the children during testing. Initial screening included visual acuity measurement of both eyes using a conventional Snellen chart, and assessment of ocular alignment with cover test, but no children with strabismus were identified. Refraction was not performed.

The 5 tests were shown in a random order and participants were allowed unlimited viewing time. The right eye of each child was tested, using occluding glasses for the left, and spectacles were worn if they had been prescribed for distance use. For each test a starting point of logMAR 0.2 (6/9.5) was used and the children were asked to name the letters or picture optotypes presented. Where children were unable to name a letter or picture optotype, they pointed to it on the matching card. For the line tests, children were asked to name each optotype in order from left to right. If all 4 logMAR 0.2 optotypes were not read correctly on initial presentation, larger optotypes were presented until all 4 optotypes were read correctly. Smaller optotypes were then presented and testing continued until 3 or more optotypes at a single acuity level were named incorrectly. If a child was hesitant, they were encouraged once to guess. Pointing at the letters by the examiner was not used under any test condition.

Each child was assessed in a single session and testing was carried out by 3 optometrists experienced in the examination of children and the tests used (including the author). Each examiner used standardized instructions and a strict protocol for testing. An analysis to look for inter-examiner variability was not carried out. Five children whose measured acuity was worse than logMAR 0.2 (6/9.5) in one or both eyes were referred for a full eye examination; however, data from these children were included in the study.

2.2.4 Data Analysis

Visual acuity data were converted into logMAR with each correctly read optotype assigned a score of 0.025. Each optotype incorrectly named, regardless of the level, resulted in the addition of 0.025 to the overall score. Mean logMAR was calculated for each group and test and data were normalized, to highlight the crowding effect, by subtracting the unflanked single optotype logMAR results (either Sheridan Gardiner Test or Single Kay Pictures Test, as appropriate) from the logMAR results of the respective crowded tests. The data were subject to one-way repeated measures ANOVA and post-hoc testing was performed, where appropriate, using the Tukey test (Statistica™, Statsoft, Tulsa USA). Mean data were used in the analysis, to look for a difference in crowding between the tests. The data from individuals may contain bias from the test order, loss of concentration and variability in the effort made with each of the tests.

In addition, an analysis using the method of Bland and Altman (1986) was carried out to look at the comparability of the 2 crowded letter tests, the logMAR Crowded Test and the Sonksen Test.

2.3 Results

Table 2.2 shows the mean logMAR and standard deviation for each test separated into the younger and older age groups. The results are plotted in Figure 2.3 where normalized logMAR is shown for each test and logMAR values greater than zero are indicative of crowding. The top panel shows results for the younger children and the bottom panel the older children.

2.3.1 Younger children

There was a significant main effect of test on acuity ($F=63.92$, $df=4$, $p<0.001$). Mean acuity was poorest with the logMAR Crowded Test and best with the single optotype tests with the mean from the Sonksen Test falling in-between. Mean acuity using the Crowded Kay Picture Test was poorer than the single optotypes tests, but better than the crowded letter tests. Post-hoc testing showed that the logMAR Crowded Test gave significantly different results to all the other tests ($p<0.001$), as did the Sonksen Test ($p<0.05$) and the Crowded Kay Picture Test ($p<0.05$). There was no difference between the Sheridan Gardiner and Single Kay Picture Tests results in this age group ($p=0.93$) (Figure 2.3).

2.3.2 Older children

In the older children, there was also a significant main effect of test on acuity ($F=63.59$, $df=4$, $p<0.001$). Mean acuity was poorest with the logMAR Crowded Test ($p<0.001$). Mean acuity was best with the single optotype tests, which were not significantly different from each other. The mean acuity with the Sonksen Test fell between the logMAR Crowded Test and the single optotype tests and was significantly different to all the other tests ($p<0.001$). In the older children, mean acuity with the Crowded Kay Picture Test was no different to that from the single optotype tests (Figure 2.3), $p=0.24$.

Table 2.2 Mean visual acuity for each test (logMAR), with standard deviation in brackets LMC, logMAR Crowded; S, Sonksen; SG, Sheridan Gardiner; CK, Crowded Kay Picture; SK, Single Kay Picture

	LMC	**S**	**SG**	**CK**	**SK**
Younger children	0.00 (0.08)	-0.07 (0.09)	-0.18 (0.08)	-0.10 (0.09)	-0.15 (0.11)
Older children	-0.04 (0.11)	-0.11 (0.11)	-0.17 (0.14)	-0.17 (0.11)	-0.18 (0.13)

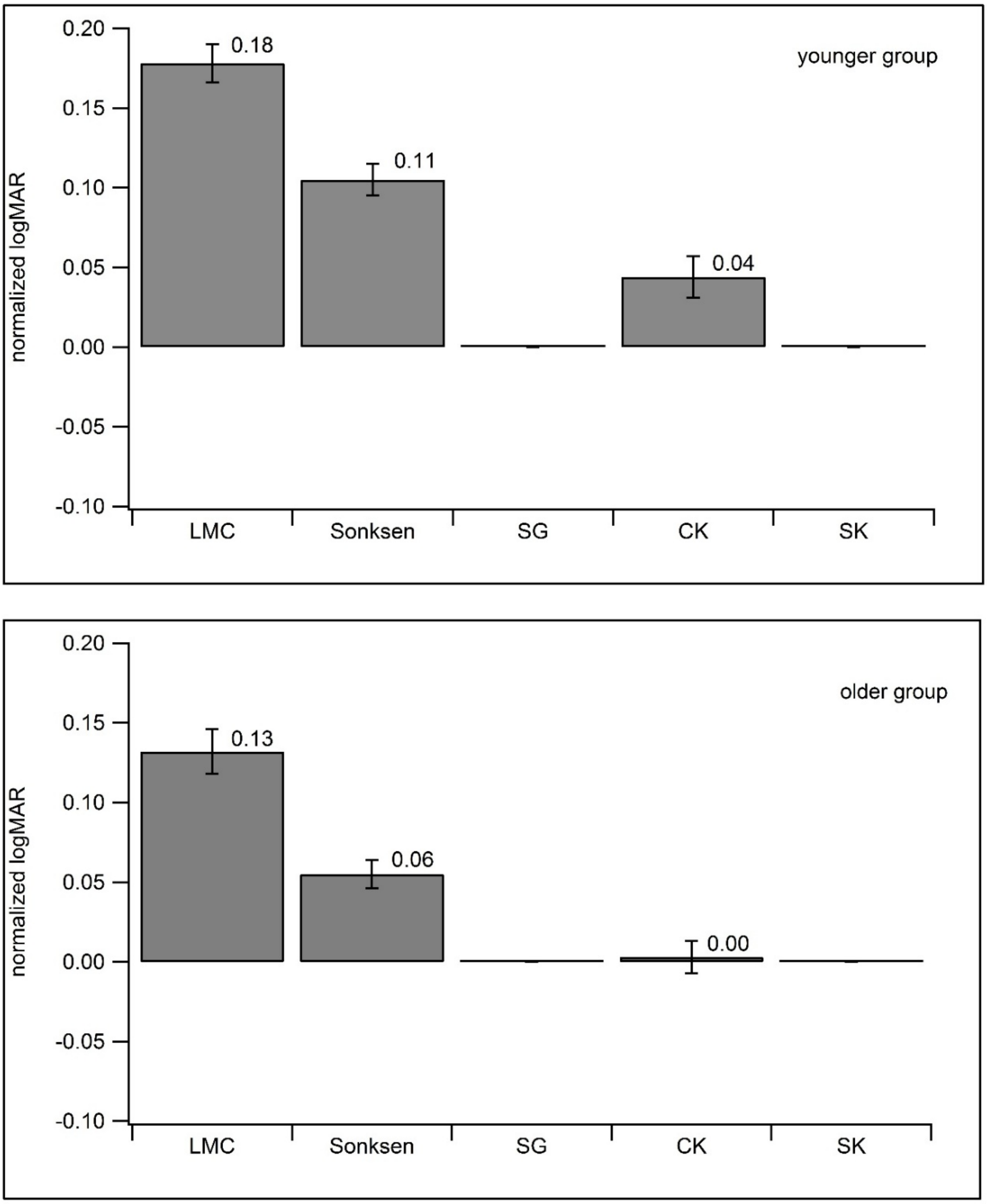


Figure 2.3 Normalized logMAR is plotted for each of the visual acuity tests to show the crowding effect. The unflanked single optotype logMAR results (either Sheridan Gardiner or Single Kay Pictures Tests as appropriate) were subtracted from the logMAR result of the respective crowded tests. The top panel shows data for the younger age group and the bottom panel for the older age group. Error bars represent ±1SE.

2.3.3 Entire group analysis

A scatterplot of the difference in acuity score against the mean acuity score was plotted to analyse the agreement between the logMAR Crowded Test and the Sonksen test, Figure 2.4 (Bland and Altman, 1986).

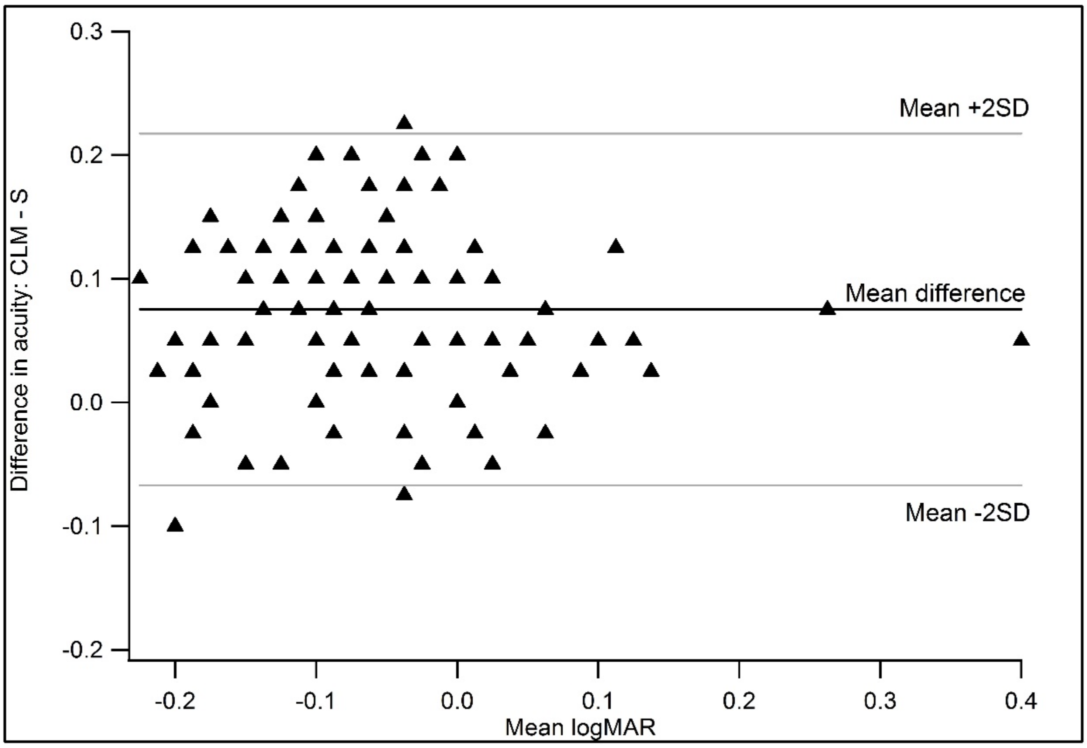


Figure 2.4 Scatterplot showing the difference in logMAR against the mean acuity for the crowded logMAR and Sonksen Tests for the 2 groups of children combined.

The mean difference in scores across all the children was 0.075 logMAR, with the Sonksen Test having better acuity than the logMAR Crowded Test. The confidence intervals plotted show that for these 2 tests, 95% of children would be expected to have just under 0.3 logMAR, or 3 lines difference between the tests. The scatterplot does not show any systematic bias towards either test with increasing logMAR.

Figure 2.5 plots the logMAR for each of the tests as a function of age. The straight lines represent linear regression fits to each data set (acuity test). Figure 2.5a shows results of the letter tests: Sheridan Gardiner Test (closed symbols and solid line), the Sonksen (open squares and dashed line) and the logMAR Crowded Tests (cross symbols and dotted line). For ease of viewing, data have been offset on the y-axis as follows: Sonksen shifted up by 0.2 logMAR and LMC shifted up by 0.4 logMAR. Figure 2.5b shows the results of the picture tests: Single Kay Pictures Test (closed symbols and solid line) and the Crowded Kay Pictures Test (open symbols and dotted line). For ease of viewing, data from the Crowded Kay Pictures Test have been shifted up by 0.2 logMAR. The slopes of the regression lines for both the uncrowded, single optotype tests were not significantly different from zero (letter tests, $p=0.71$; picture tests, $p=0.15$). However, the slopes were significantly different from zero for all three crowded tests (LMC $p<0.05$, S $p<0.05$, CK $p<0.01$).

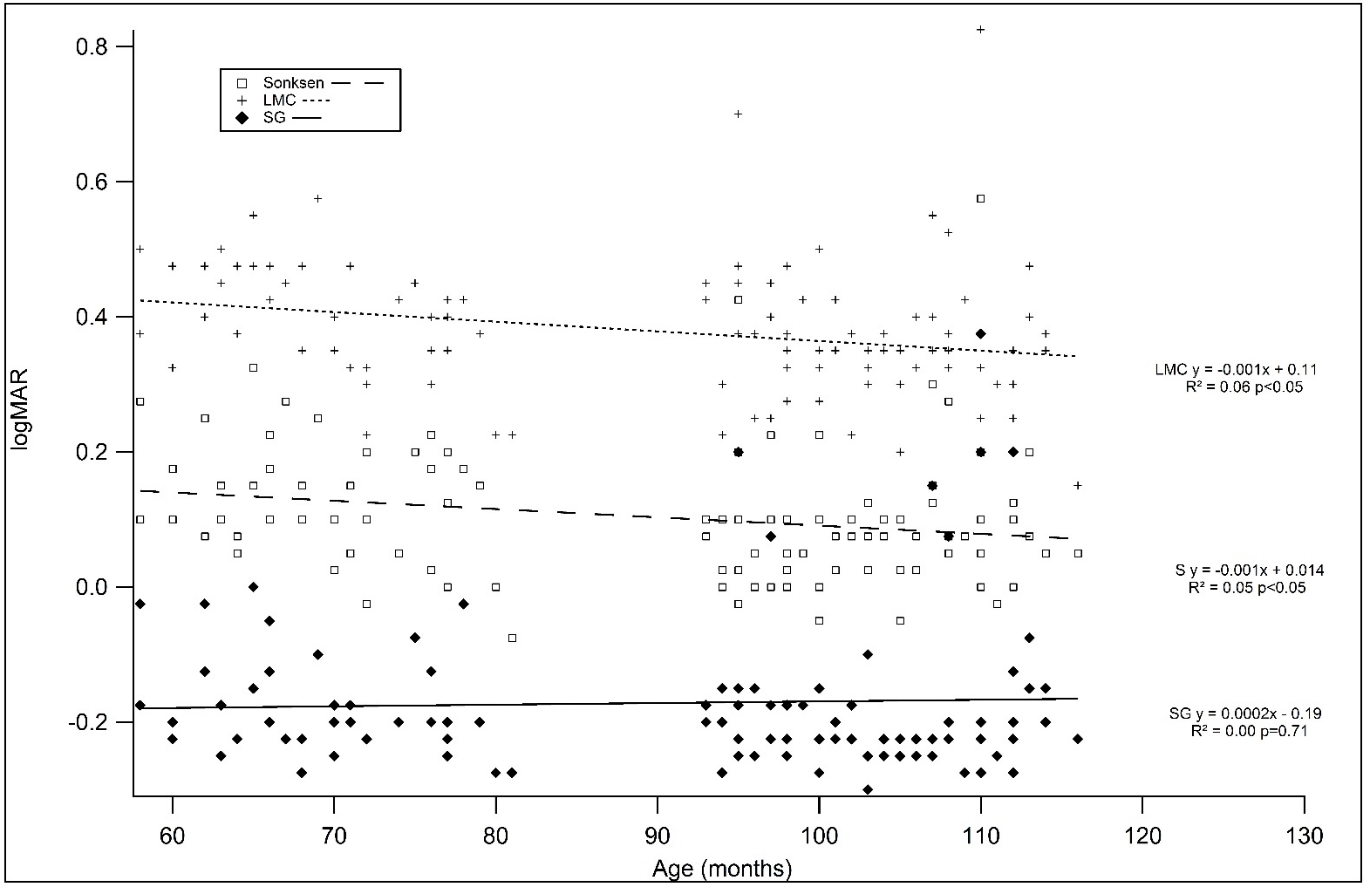


Figure 2.5a. LogMAR is plotted as a function of age in months for the 3 letter tests: Sheridan Gardiner Test, SG, (closed symbols and solid line), Sonksen, S, (open squares and dashed line) and the logMAR Crowded Tests, LMC, (cross symbols and dotted line). The straight lines represent linear regression fits to each data set (acuity test). For ease of viewing, data have been offset on the y-axis as follows: Sonksen shifted up by 0.2 logMAR and LMC shifted up by 0.4 logMAR.

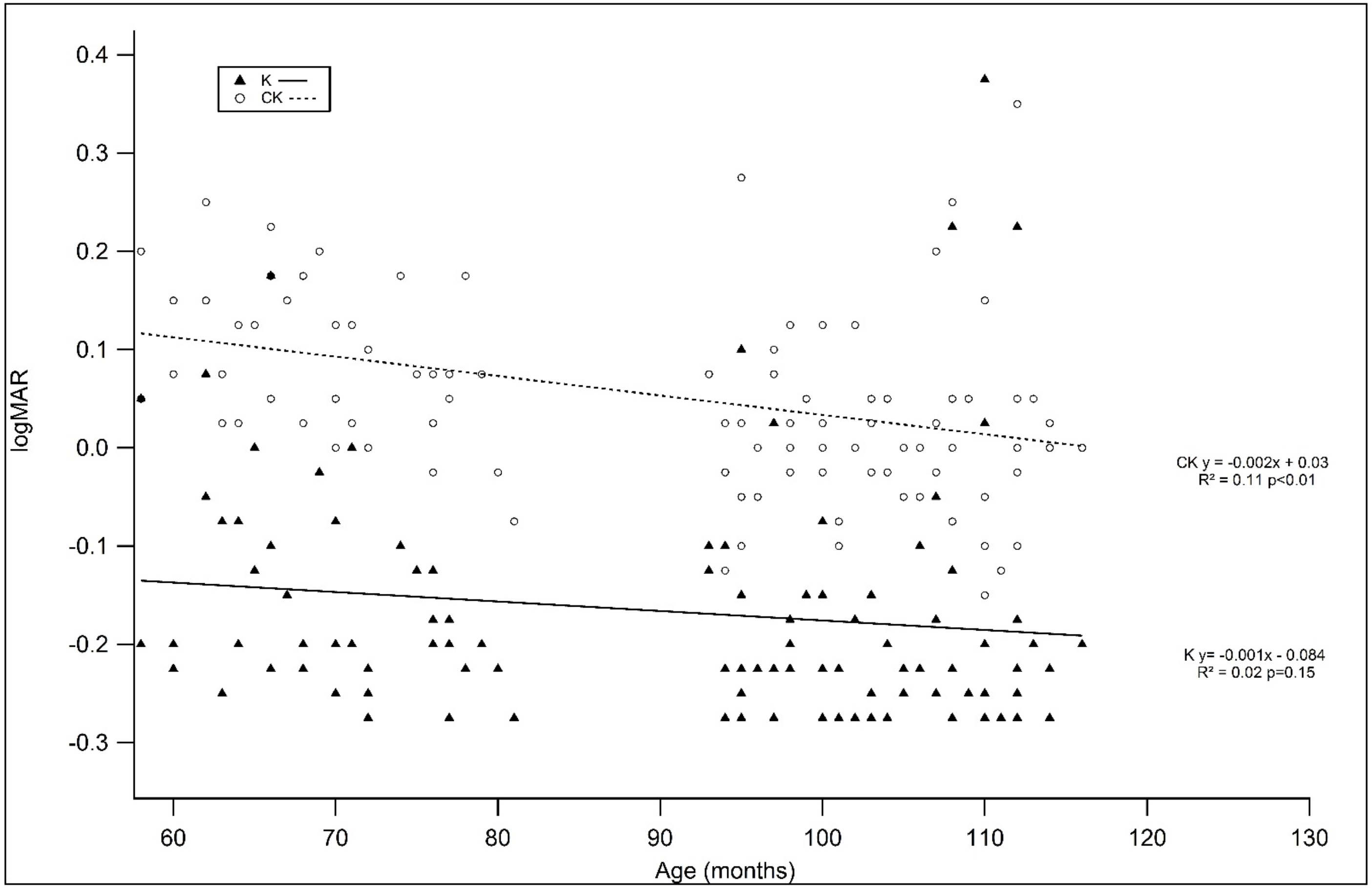


Figure 2.5b LogMAR is plotted as a function of age in months for the 2 picture tests: Single Kay Pictures Test, K, (closed symbols and solid line) and the Crowded Kay Pictures Test, CK, (open symbols and dotted line). The straight lines represent linear regression fits to each data set (acuity test). For ease of viewing, data from the CK test have been offset on the y-axis by adding 0.2 logMAR.

2.4 Discussion

2.4.1 Comparison of letter tests

The general level of visual acuity in our sample is consistent with published age norms (Sonksen et al., 2008) and despite not screening for refractive error, the mean Sheridan Gardiner (i.e. single letter) acuity in both younger and older groups of children was better than 6/5 (logMAR -0.1, Table 2.2). Our results are also consistent with previous studies reporting that children perform better in uncrowded than crowded visual acuity tests (Simmers et al., 1997, Youngson, 1975, Hilton and Stanley, 1972, Morad et al., 1999) Although visual acuity was poorest with the logMAR Crowded Test in both younger and older children, younger children exhibited a greater loss in visual acuity relative to the Sheridan Gardiner Test results. There was also a significant difference in visual acuity between the Sonksen and Sheridan Gardiner Tests for both groups (albeit not as large) and once again the younger children exhibited a greater loss with the Sonksen Test relative to the Sheridan Gardiner Test results. These results show that while both groups of children exhibited poorer visual acuity with the crowded visual acuity tests, the two crowded letter tests used were not equally effective at inducing crowding and the crowding effect was greater in the younger group of children suggesting an age dependent effect.

Using the method of Bland and Altman (1986), it was shown that across both groups of children, there is a 95% confidence interval of agreement of around 3 lines between the logMAR Crowded Test and the Sonksen Test. Clinically, comparability between 2 similar tests would ideally be closer than these findings.

2.4.2 Comparison of picture tests

Results using the Kay Picture optotypes were generally similar; the Crowded Kay Picture Test resulted in poorer visual acuity when compared to the Single Kay Picture Test, but only for the younger children. There was no significant difference in visual acuity between the Crowded Kay Picture Test and the Single Kay Picture Test in the older children, indicating that in older children the Crowded Kay Picture Test did not induce significant crowding (Figure 2.3).

2.4.3 Viewing distance

We used two different viewing distances, 3m and 6m, depending on the test. In testing young children, the closer 3m distance enhances rapport and helps maintain attention (Salt et al., 2007, Sheridan, 1970, Atkinson et al., 1988); however, as our 6m viewing distance used a mirror, the examiner could stand beside the child and hence maintain the advantages of proximity to the child. There is some evidence that a nearer testing distance yields slightly better acuity, (Rozhkova et al., 2005, Lippmann, 1971) although Atkinson et al. (1988) found no significant difference in either single or multiple letter acuity, or in the crowding effect when measured at 3m and 6m in 3-4 year olds. It is possible that for some of our participants, the 3m testing distance conferred a small advantage for the LogMAR Crowded Test and the Sonksen Test. Had a 6m viewing distance been used, measured VA could have been worse, hence increasing the difference between these crowded tests and the Sheridan Gardiner Test. So the greater crowding effect we found in the LogMAR Crowded Test and the Sonksen Test cannot be explained by the decreased viewing distance used.

2.4.4 Effect of age

Our single optotype results, showing no effect of age in the range used (4-9 years), suggest that uncrowded acuity is mature at an earlier age than crowded acuity. This accords with the conclusions of Jeon et al. (2010) and Semenov et al. (2000) However, the age at which maturity of single optotype acuity occurs differs between the studies. We found no improvement in uncrowded acuity between our younger and older children, whereas Jeon et al found a significant improvement from the ages of 5 to 8.

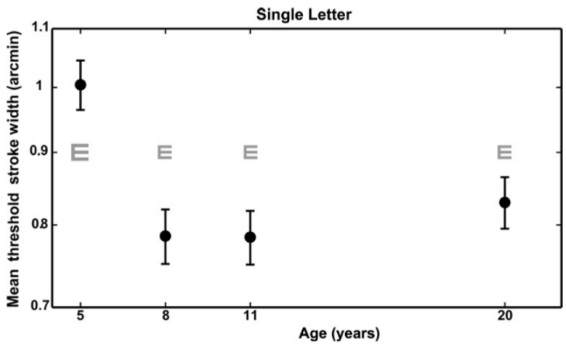


Figure 2.6, after Jeon et al. (2010), showing single letter acuity as a function of age for E targets.

Comparison of acuity results showed that our younger children had better acuity than those similarly aged children in the study by Jeon *et al*, where the mean logMAR of their 5 year olds was around 0, for E targets (reproduced above as Figure 2.6), compared to our -0.18 (Sheridan Gardiner Test). Differences in the targets between the current study and theirs could be a possible explanation, and the fact that all the children in our study were at school and used to reading letters, whereas the orientation discrimination of the letter E in the Jeon et al study may represent a more difficult task. Bondarko and Semenov (2005) showed the E target to be generally more difficult for children compared to the Landolt C. Our results also suggest that crowded and uncrowded acuity do not develop in parallel (Fig. 2.5). Although this appears to conflict with the conclusions of Kothe and Regan (1990) (see Chapter 1, section 1.4.1), the linear letter acuity tests in our study have more contour interaction, because of closer inter-letter and letter-surround box separation, than the Snellen test used by Kothe and Regan (1990), therefore making our line tests harder.

The improvement in crowded visual acuity with age (Figure 2.5) is likely to reflect the development of underlying factors that contribute to the total crowding effect; the influence of contour interaction, the effect of gaze instability and/or attentional factors (Flom, 1991). On this basis, the decrease in crowding with age could result from a change in the magnitude and/or extent of contour interaction, better control of gaze, or a maturation of attention and general cognitive abilities with age or some combination of all three factors.

2.4.5 Contour interaction and age

There is evidence that the shape of the contour interaction function in young children is similar to that of adults, with the maximum effect occurring at a similar target-flanker separation distance in children and adults (Manny et al., 1987). Studies which investigated the furthest distance of flanker from target at which an effect can be measured (Semenov et al., 2000, Jeon et al., 2010), have shown that contour interaction occurs over larger distances in children than in adults. This finding helps to explain differences in acuity between the two crowded letter tests used in our study. The LogMAR Crowded test which resulted in the poorest acuity has the closer inter-optotype separation (0.5 letter widths) and, therefore, more contour interaction than the Sonksen Test which has an inter-optotype spacing of one letter width. The mean difference of 0.07 logMAR between these two tests (in both age groups) is greater than the mean difference in visual acuity found in adults when the inter-letter separation is changed from 1.0 to 0.5 letter- widths (Shah et al., 2010). Our finding thus supports the hypothesis that contour interaction has a greater effect (magnitude) in children than in adults. A surprising outcome was that the Crowded Kay Pictures Test resulted in significantly better mean acuity than the LogMAR Crowded Test, despite a similar inter-optotype spacing of 0.5 optotype widths. It is possible that the Kay Picture optotypes do not induce as much contour interaction as letters for the same inter-optotype separation, which may also explain previous results where Crowded Kay Pictures were found to be slightly easier than letter acuity tests (Elliott and Firth, 2007, Jones et al., 2003). The sizing of the Kay Picture optotypes was developed empirically to give an acuity equivalent to that of a Snellen chart (Kay, 1983). However, presumably because of their relative complexity or unfamiliarity, the Kay Picture optotypes are twice the size of the corresponding letter optotype at a given acuity level. As their spacing in the crowded test is a proportion of the optotype size, the angular separation between optotypes will be larger than in the letter tests in this study. If foveal contour interaction occurs within a fixed angular zone, as is argued by Siderov et al. (2013), the greater separation of the Kay picture optotypes in arc minutes could be a contributing factor to the reduced contour interaction in this test. Thus, a clinician using a picture test with 0.5 optotype-widths' separation should not make the assumption that the contour interaction will be equivalent to a letter test with 0.5 letter-widths' separation.

One of the factors governing the extent to which optotypes induce contour interaction has been shown to be their similarity with the target optotype (Kooi et al., 1994) and it could be that the Kay picture optotypes are dissimilar enough from each other not to exhibit contour interaction in the same way as letter optotypes. Additionally, contour interaction is governed by the leading edge of a distracter (Flom, 1991, Takahashi, 1968) and in using pictures as optotypes, there will be variation in the shape of the edge of the picture; not all will have a strong leading edge, such as a vertical line. Contour interaction in picture optotypes was successfully demonstrated by Mayer and Gross (1990) who modified the Allen Pictures optotypes by adding distraction bars and demonstrated crowding in isolated, surrounded pictures. However, they used a separation between optotype and distracter of between 0.1 and 0.2 times the picture size, a closer separation than used in the Crowded Kay Pictures Test.

2.4.6 Eye movements and age

Based on recent evidence that there is no significant change in the extent of contour interaction across an age range similar to one we used (Jeon et al., 2010), the difference in mean acuity between the LogMAR Crowded Test and the Sonksen Test may be explained by contour interaction; however, an alternative explanation is needed for the age-related improvement in crowded line acuity. In the study by Jeon et al*,* recognition of the target did not require sequential fixation from one optotype to the next along a line (single optotypes were used) (Jeon et al., 2010). On this basis, the decrease in crowding found with the acuity tests in our study might be explained by the underlying development of more accurate gaze control in children and the development of fixational eye movements. There is some evidence from direct measurement of children's eye movements that fixational stability is immature in young children (Kowler and Martins, 1982, Aring et al., 2007); however this does not constitute evidence that the retinal smear from poor fixation is the cause of reduced acuity. Kothe and Regan (1990) proposed that failure of some normally sighted young children to achieve adult levels of line acuity may be attributable to a delayed development of gaze selection rather than cognitive factors or contour interaction. Their evidence came from the finding that some 4-5 year olds had better acuity measured on a repeat letter chart, which minimizes the requirement for accurate gaze control, than on a Snellen chart.

The influence of gaze control may provide another possible explanation for the relatively lower levels of crowding found using the Crowded Kay Pictures Test. The Kay picture optotypes by virtue of their relative size, subtend a greater angular extent for the same stated acuity than the letter charts. Therefore, Kay Pictures spaced at 0.5 inter-optotype separation will have twice the angular separation as letter optotypes measured in units of arc mins at the same acuity level. A young child reading a row of optotypes just above their threshold acuity and near their physiological limit of gaze control may find the picture test easier than the equivalent letter one because of the greater angular separation of the optotypes.

2.4.7 Attention and age

The findings of our study are consistent with the hypothesis that the reduction in crowding with age is attributable to either improving oculomotor control or to a maturation in cognitive or attentional factors. Whilst the contribution of attention to crowding has been shown to be less with foveal compared to peripheral viewing (Leat et al., 1999), the mechanisms of selective attention in children are thought to be less mature in children than in adults (Bondarko and Semenov, 2005). The behavioural response of children when faced with a recognition task near their threshold of acuity may also vary with age. When a test is perceived as being more difficult, a child may refuse to respond, whereas an adult may attempt the task thereby improving their score.

2.4.8 Possible truncation

Despite ensuring that the optotype sizes of all of our tests extended to logMAR -0.3 (6/3), a possible truncation effect may still have occurred. Where a smaller line (-0.4) was available in the Crowded Kay Pictures Test, some of the children achieved one or more optotypes of this size. Therefore it is possible that truncation of acuity could have occurred for some children with exceptionally good acuity. In those cases, in the tests where there may have been a truncation effect, the Sheridan Gardiner Test and the two Kay Pictures Tests, we re-analysed the data after assigning an additional two optotypes to any child who correctly named 1 or more optotypes on the lowest acuity level. Our re-analysed results of the linear regression still showed that the slopes of the two single optotype tests were not significantly different from zero, as depicted in Figure 2.3, whilst for all three crowded tests the slopes were significantly different from zero ($p<0.05$). ANOVA and post-hoc testing gave similar results to before, the only difference with the remodelled data being that in the younger children, acuity from the Crowded Kay Pictures Test was not significantly different to the Sonksen Test ($p= 0.10$). Therefore, it was judged that any truncation effect present was small and does not alter our main findings and conclusions.

2.4.9 Effect of inclusion of data from all participants

Data from all participants were included in the study to look for a difference in crowding between the crowded tests. By normalizing data to the respective uncrowded test, the presence of a few participants with uncorrected refractive error did not matter. However, in the analysis of logMAR against age (Figure 2.5), a greater number of uncorrected myopes in the older group might have masked improvement in logMAR with age. The data were therefore remodelled with the exclusion of any participants whose logMAR on the Sheridan Gardiner test was 0.15 or worse. Five participants were excluded and the data were plotted in Figure 2.7 and fit with linear regressions. The overall conclusion that crowded and uncrowded acuity do not develop in parallel still held, with a slower development of uncrowded than crowded acuity.

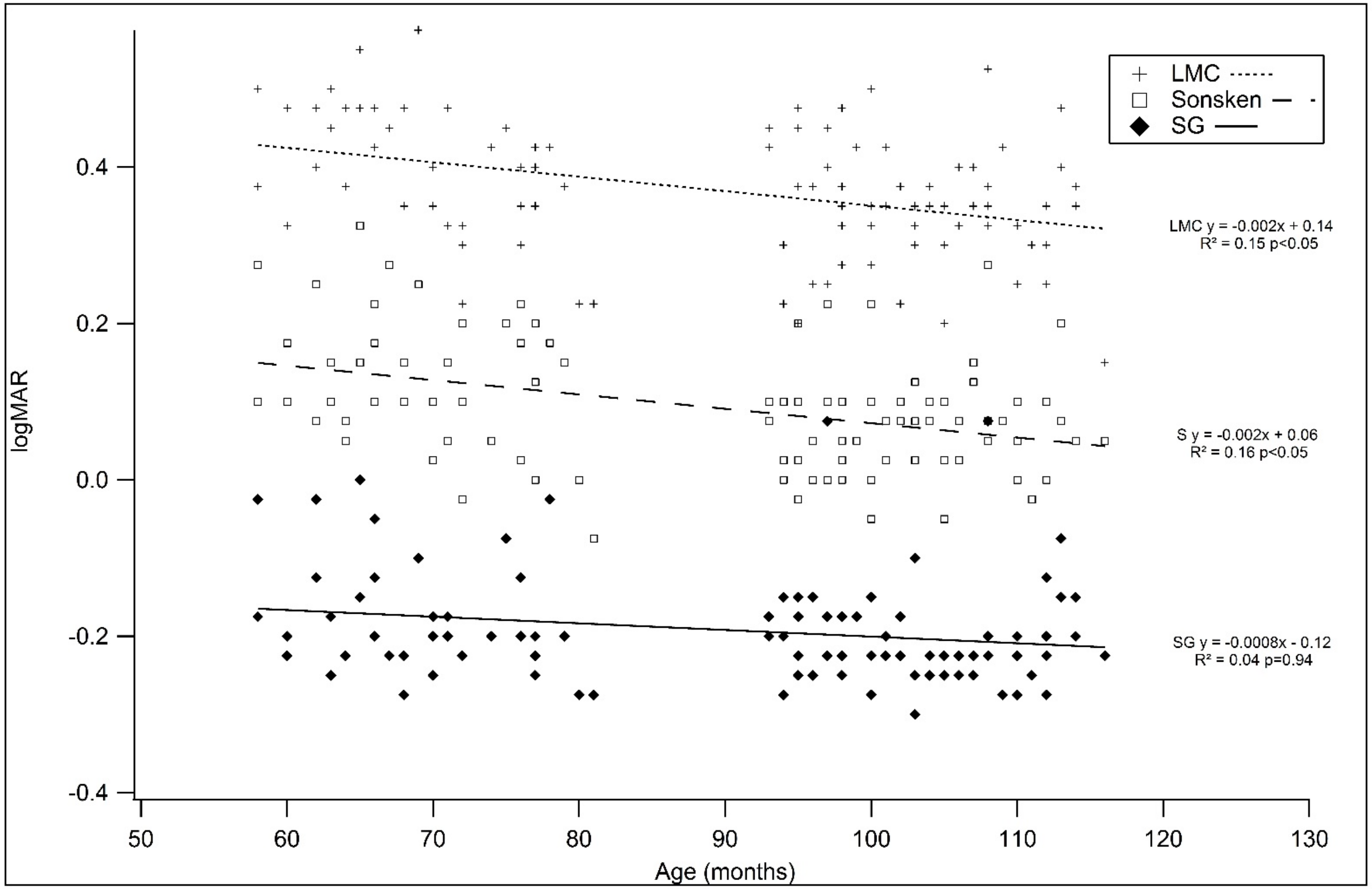


Figure 2.7a. LogMAR is plotted as a function of age in months for the 3 letter tests, with the exclusion of 5 participants: Sheridan Gardiner Test, SG, (closed symbols and solid line), Sonksen, S, (open squares and dashed line) and the logMAR Crowded Tests, LMC, (cross symbols and dotted line). The straight lines represent linear regression fits to each data set (acuity test). For ease of viewing, data have been offset on the y-axis as follows: Sonksen shifted up by 0.2 logMAR and LMC shifted up by 0.4 logMAR

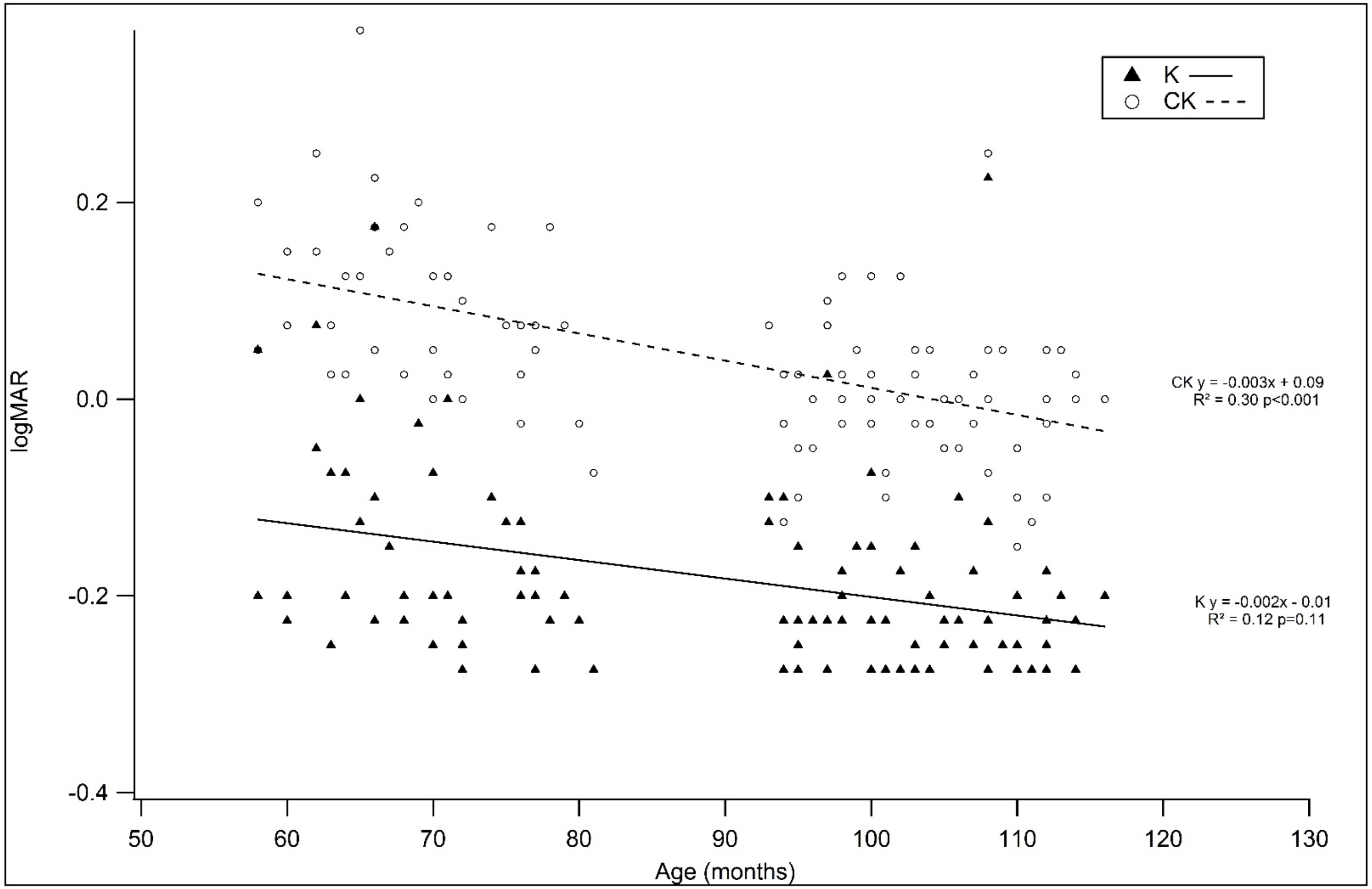


Figure 2.7b LogMAR is plotted as a function of age in months for the 2 picture tests, with the exclusion of 5 participants: Single Kay Pictures Test, K, (closed symbols and solid line) and the Crowded Kay Pictures Test, CK, (open symbols and dotted line). The straight lines represent linear regression fits to each data set (acuity test). For ease of viewing, data from the CK test have been offset on the y axis by addition of 0.2 logMAR.

2.4.10 Conclusions

In conclusion, our results are consistent with the literature, showing that, in general, single, unflanked optotype tests, letter or picture, overestimate visual acuity compared to crowded acuity tests. However, crowding in the Crowded Kay Pictures Test is less robust than in letter optotype tests with a similar format, which may reduce sensitivity of the Crowded Kay Pictures Test compared to letter optotype tests particularly if used in older aged children. The results show poorer mean acuity using the crowded tests in the younger children and, given that less change in the single optotype acuity was shown across the age range, this indicates that in normally sighted children, there is still maturation of line acuity taking place between the ages of 4 and 10. This maturation is likely to be a result of an improvement in gaze control or a maturation of selective attention or cognitive factors. As crowded tests are used to measure progress of amblyopia treatment, it is important to understand whether improvement in visual acuity over time is as a result of the treatment or merely because of an age-related reduction in crowding.

Chapter 3

Test chart design considerations

3.1.1 The need for custom-designed tests

The results of the study described in Chapter 2 showed an age-related reduction in the magnitude of crowding with age. They also showed a greater crowding effect in the LogMAR Crowded Test than the Sonksen logMAR Test presumably because of the closer spacing of letters. Crowding was found to be less robust in the Crowded Kay Pictures Test, particularly in the older children, presumably because size and spacing of the optotypes is not the same as in the equivalent sized letter tests.

A goal of this thesis is to disentangle the effects of contour interaction, eye movements and divided attention and their relative contributions to the overall crowding effect. This is important because the design and format of a crowded test will determine whether the 'crowding' is simple contour interaction with bars or a box surrounding a single target letter, or a crowding effect which includes an eye movement component, and/or divided attention (Flom, 1991, Atkinson, 1991). Maturation of these components of the crowding effect may have different timescales in children, so judgements regarding 'normal crowded acuity' at any particular age need to be underpinned by an understanding of how the chart features interact and contribute to the overall crowding effect.

Using fixed, commercially available visual acuity tests limits the types of comparisons that can be made between different tests and can limit the ability to test more specific hypotheses. For example, the tests with single optotype presentation had no crowding features and the linear tests had both contour interaction from neighbouring features as well as requiring fixation between optotypes. Moreover, the central letters in the line tests were flanked by the surround box top and bottom and by other optotypes on either side and the end optotypes by a box on 3 sides and an optotype on one side (see Figure 2.1). These issues did not allow us to separate

- the effects of target-flanker separation in a single flanked optotype from a linear presentation and
- the effect of using a bar or box vs other optotypes to crowd the target optotype.

As a result of these types of limitation, a number of custom designed tests were created. These new test designs allowed the following to be varied independently:

- contour interaction- by the presence and spacing of nearby contours
- optotype presentation- single or linear
- target-flanker similarity- use of bars or other letters as crowding features.

This will enable the relative contributions of contour interaction, eye movements and attention to the overall crowding effect to be determined.

3.1.2 Choice of optotype

The Sloan letter set (Sloan, 1959) was chosen to create the custom letter tests. The Sloan letters are recognised as an alternative to the Landolt C for the specification of visual acuity standards (National Academy of Sciences-National Research Council Committee on Vision, 1980) and are commonly used in visual acuity testing and feature extensively in the literature, e.g. (Alexander et al., 1997, Raasch et al., 1998, Ravikumar et al., 2003, Miller et al., 2001, Carkeet et al., 2008). The 10 letters in the set are C, D, H, K, N, O, R, S, V and Z and they are constructed in a 5x5 format, with the height and the width of each letter 5x times the stroke width.

Individual relative legibility of each Sloan letter differs by no more than 12% from the mean relative legibility of the set (Sloan et al., 1952).

3.2 Design of tests

3.2.1 Extent of contour interaction

To investigate simple contour interaction, test presentations were designed using single optotypes surrounded by 4 flanking bars at different optotype to flanker separations. The length and width of flanking bar used is discussed later in this chapter. The edge-to-edge target-flanker separations were 0.25, 0.5, 1.0 and 1.5x optotype size to encompass critical spacing found in other studies (Manny et al., 1987, Flom et al., 1963b, Jeon et al., 2010, Semenov et al., 2000) (Figure 3.1). Although it is known from the literature that critical spacing is greater in children than adults (Jeon et al., 2010, Semenov et al., 2000, Matsumoto et al., 1999), its extent depends on experimental design and targets used, so the letter target with simple bar flankers at varying distances from the letter was included to evaluate the extent of contour interaction within the current study design. Visual acuity measured using unflanked letters was included to normalize subsequent results and minimize a potential confound between optotype size and letter-flanker spacing (Levi, 2008). The study was designed in the context of clinical visual acuity measurement, in which crowded visual acuity tests use crowding elements at a distance proportional to optotype size.

A participant with poor gaze control may foveate one of the flanking bars rather than the letter, but as the flanking bar does not resemble any of the 10 Sloan letters, it is assumed that the participant will continue to look for the target letter. Thus, the main contribution to crowding is this target/flanker configuration is contour interaction.

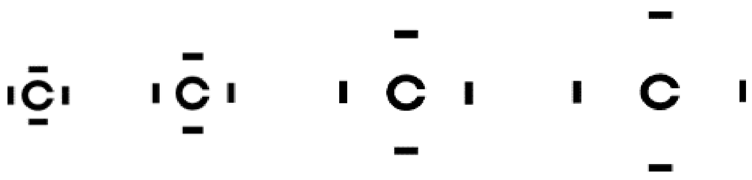


Figure 3.1 Example presentations of a Sloan letter C with flanking bars at edge-to-edge separations of 0.25, 0.5, 1.0 and 1.5 letter-widths.

3.2.2 Effect of gaze control

Commercially available crowded visual acuity tests present optotypes either singly or in linear format (Anstice and Thompson, 2014, Friendly, 1978). In linear tests which display a single line of letters with a box surround, such as the logMAR Crowded Test or the Sonksen Test, any resultant crowding is presumably derived from a number of factors including the influence of adjacent neighbouring letters, the need to read the letters correctly from one to another and the influence of the surrounding box. In order to investigate the effect of linear presentation on crowding, without the confound of mixed flanking elements, a linear format test was produced which retained the crowding bars between letters. Edge-to-edge letter-flanker separation was 0.5 letter widths, so in this presentation, the distance between neighbouring letters was 6 stroke widths (5 stroke widths plus the flanker thickness). For this and the other tests produced for the different experimental conditions, the edge to edge separation of letter and flanker was kept constant at 0.5 letter-widths, a separation where contour interaction has previously been demonstrated in both adults and children (Semenov et al., 2000, Jeon et al., 2010, Manny et al., 1987, Flom et al., 1963b). This will enable the depth, or magnitude of crowding to be compared between conditions, based on a fixed contour interaction.

Figure 3.2 Example presentation of a display of 5 Sloan letters in linear format, with flanking bars. Letter-flanker separation is 0.5 letter-widths.

3.2.3 Effect of attention (letter-flanker similarity)

Atkinson (1991) showed more crowding in children's foveal vision when letters rather than a box were used to crowd the target letter. Her results may be explained by an influence of attention which was more pronounced when letter flankers were used instead of a surrounding box. In order to explore this effect more fully, test presentations were designed using letter instead of bar flankers, in both single and linear format (Figure 3.3). The letter flankers represent an increased attentional demand over the bar flankers because letter flankers are categorically similar to the target letters. The task for the first presentation is to name the middle letter only and in the second presentation, to read the middle line of letters from left to right. Only the central 5 letters are scored as the end letters are flanking letters. Because the task requires the participants to name the end letters of the linear presentation all letters on the middle line are Sloan letters. Non-Sloan letters are used for the other flanking letters.

Figure 3.3 Example presentation of single and linear displays with letter flankers. Edge-to-edge separation of letters was 0.5 letter-widths.

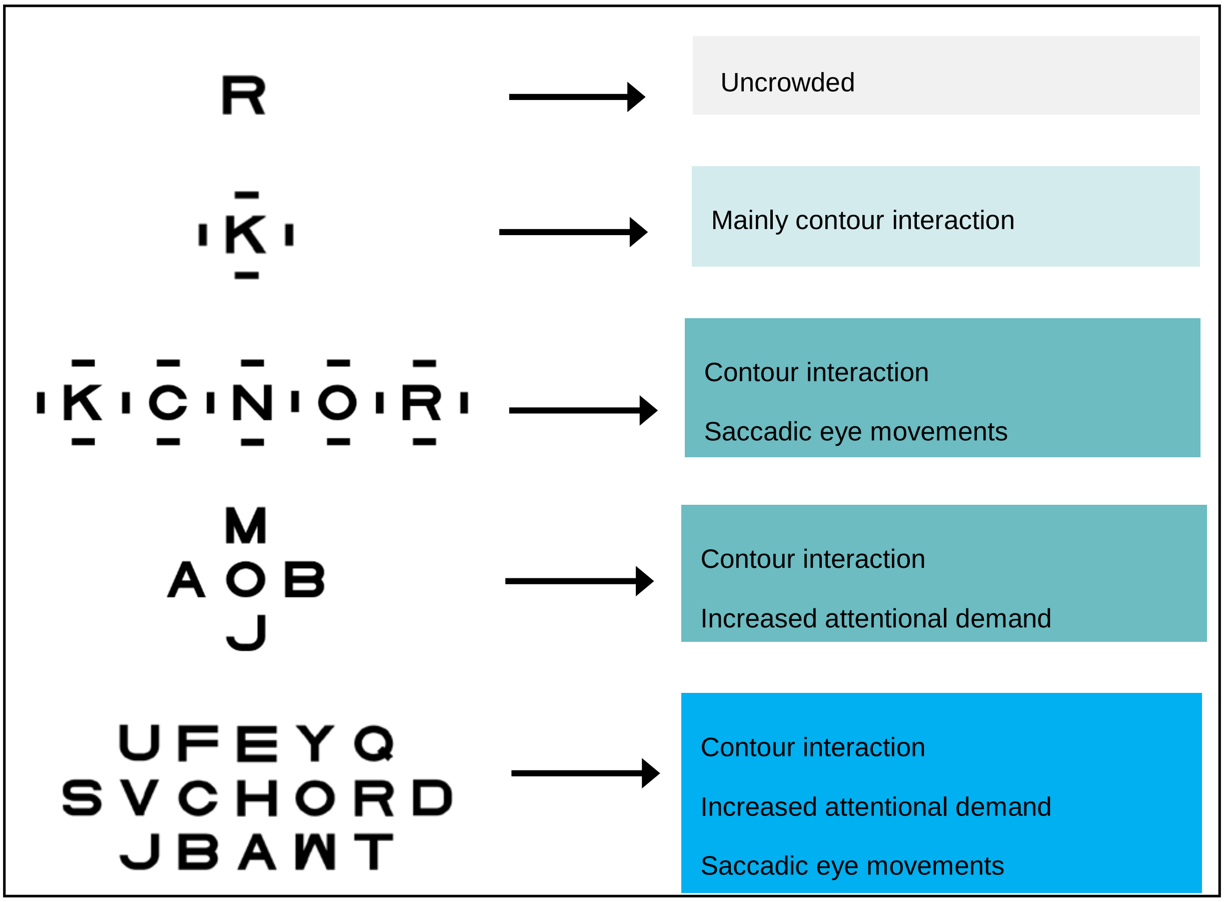


Figure 3.4 shows examples of the custom designed tests with the contribution of each format to the overall crowding effect. Linear formats require sequential fixation from letter to letter, while letter flankers represent a greater attentional demand than bar flankers.

3.3 Scoring

The acuity range of the tests was logMAR 0.4 to logMAR -0.4, the smallest size being included to avoid truncation. For each level of acuity, 5 letters were scored in each test. In the single letter presentations, 5 different letters of the same size were shown consecutively. A 0.05 logMAR progression between lines was adopted and letter by letter scoring used in order to increase sensitivity to differences between the tests (Arditi and Cagenello, 1993, Bailey et al., 1991). A score of 0.01 log unit was therefore assigned to each correctly named letter. Three out of 5 letters named correctly was chosen as the criterion for progressing. Carkeet (2001) compared variability of visual acuity measurement in logMAR charts using various termination rules and found the lowest standard deviation with termination after 4 errors. For this study, the disadvantage of increased testing time for the 4 errors criterion was judged to outweigh the possible advantage.

A results spreadsheet was produced, whereby for each test, all the correct responses were displayed with the option for the examiner to either mark these as read correctly or to record the incorrect response. As the results were entered, an indication was given when the termination criterion had been reached and logMAR was calculated for each test.

3.4 Other presentation formats considered

Previous studies have deployed other strategies to separate the effects of gaze control from contour interaction. Repeat letter charts present the target letter multiple times in a square matrix, surrounded by several lines of assorted letters (Regan et al., 1992, Kothe and Regan, 1990). Use of repeat letter charts was considered for the current study as it excludes any disadvantage of poor fixation. Another possible strategy is Rapid Serial Visual Presentation (RSVP), where words or letters are presented individually at one place in the visual field, again eliminating the need for saccades (Gilbert, 1959). However, the single and linear formats described above more closely resemble test formats commonly used clinically and may more easily highlight the effect of test chart format in a clinical context. The chosen formats were able to answer the specific research questions posed. Use of an eye tracker was also considered to measure saccades and fixation directly, but the available instrumentation does not have sufficient accuracy to enable the saccades between letters at threshold size to be measured.

3.5 Production and display of tests

The tests were produced using Adobe Illustrator CS5 (Adobe Systems Incorporated) and the Sloan font was downloaded (Pelli et al., 1988). The production of each test began with the 0.0 logMAR letter. The size of the letter was determined as follows: for a 6m viewing distance, each limb should subtend 1’ of arc and the letter should subtend 5’of arc. The height of the letter is therefore tan (5’) x 6000 = 8.73mm. The viewing distance used was 4m, so the size of the 0.0 logMAR letter is 8.73 x 4/6 = 5.82mm. Figure 3.5 shows a screenshot of the Adobe Illustrator programme, where a Sloan letter R of height and width 5.82mm has been created. The stroke width is one fifth of the letter height. Subsequent features on the display can be accurately placed using a series of ‘guides’, shown in blue in Figures 3.6 and 3.7. Any of the guides can be assigned as the origin and subsequent guides can be placed at a defined distance away, horizontally or vertically. Figure 3.6 shows an example of the Sloan letter ‘R’ with a horizontal guide placed along its top edge and assigned as the origin. Another guide, shown in darker blue has been positioned at half a letter width (2.91mm) above the origin to mark the position of lower edge of the top flanking bar. This value, in mm, can be specified to 2 decimal places. Figure 3.7 shows the display with a Sloan letter and 4 flanking bars. Guides were removed when the display elements had been placed.

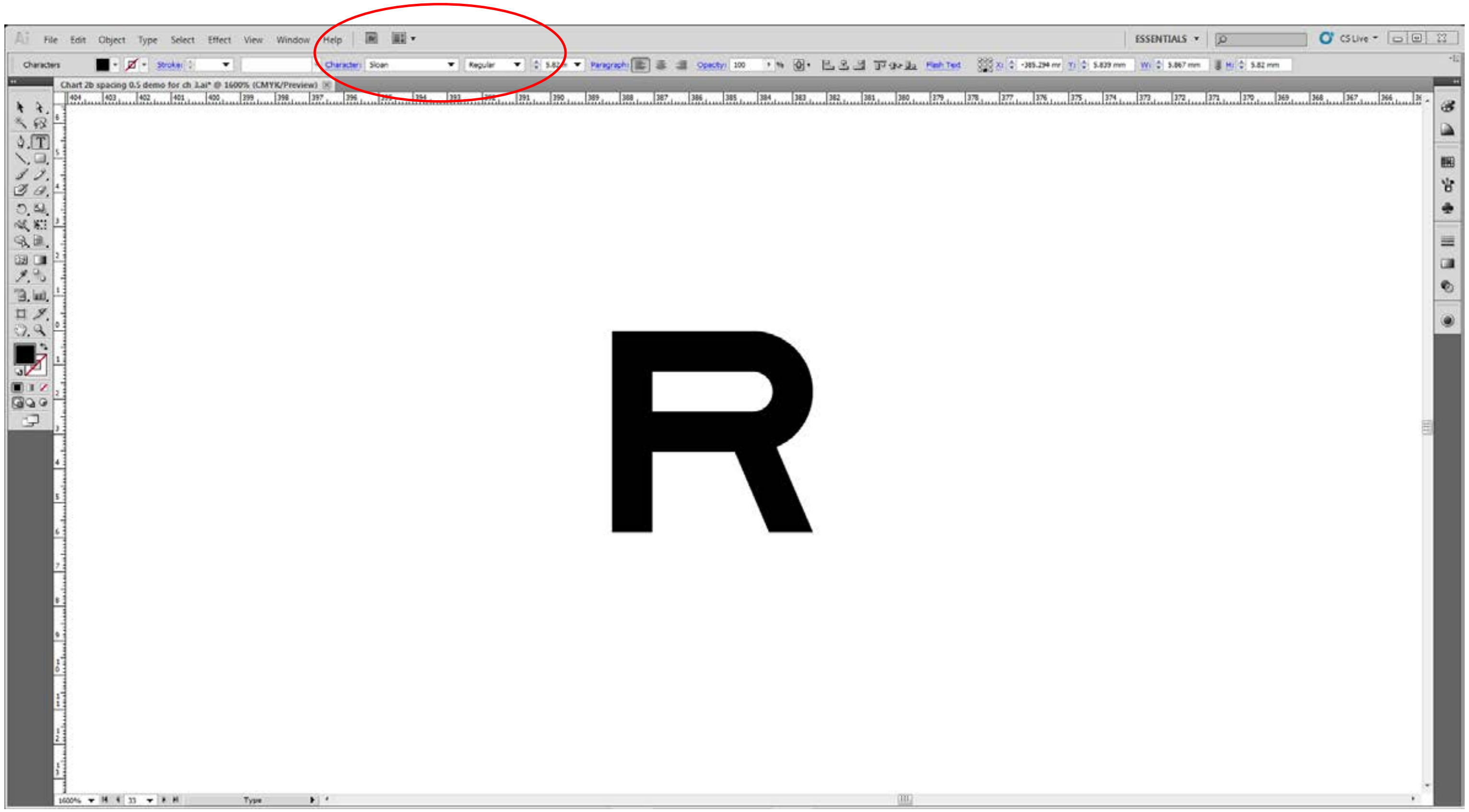


Figure 3.5 shows a screenshot of the Adobe Illustrator programme showing a Sloan letter ‘R’. The red oval indicates the font and size of the letter.

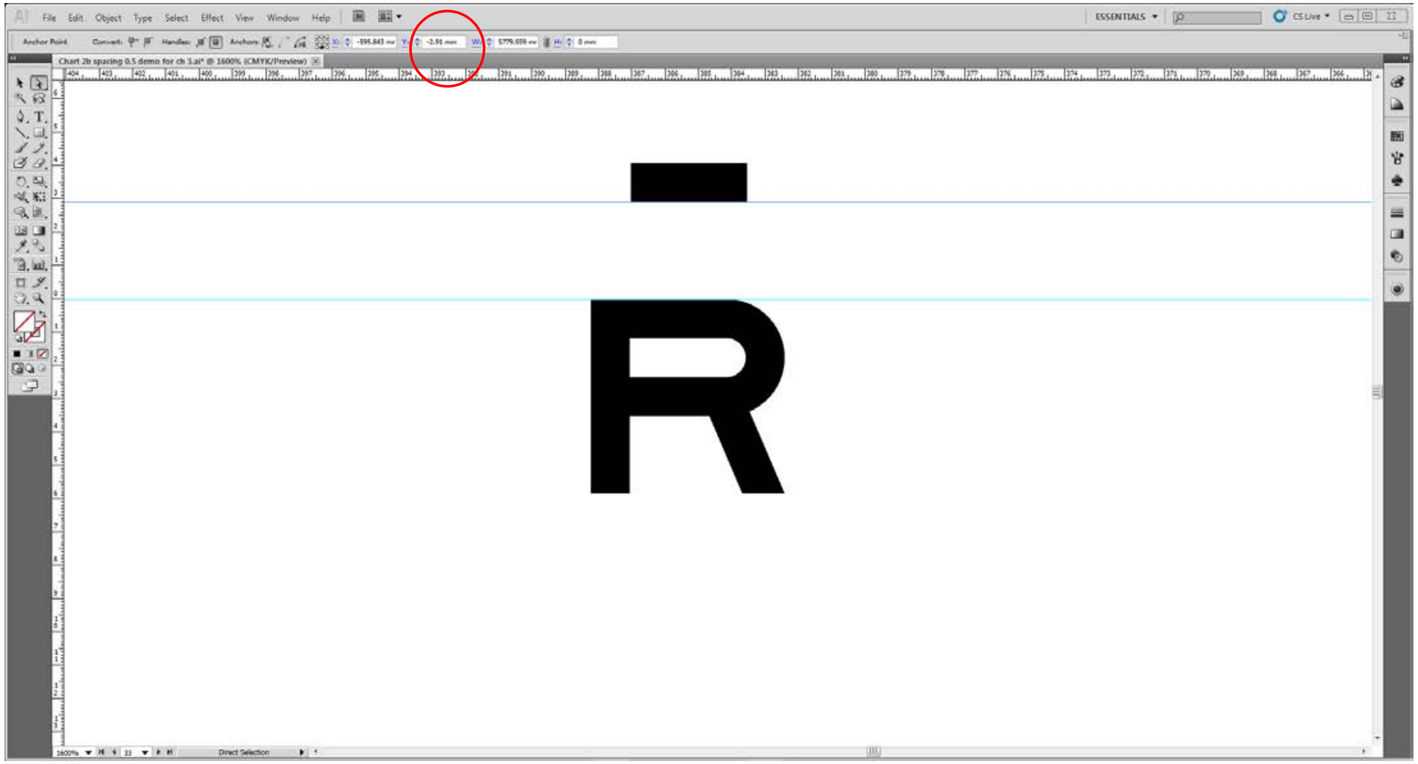


Figure 3.6 shows another screenshot of the Adobe Illustrator programme showing how an upper flanking bar can be placed accurately at a given distance from the letter. The darker blue guide has been placed a distance of 2.91 mm above the top of the letter. The red circle indicates the distance of the dark blue guide from the origin, which has been set as the top of the letter.

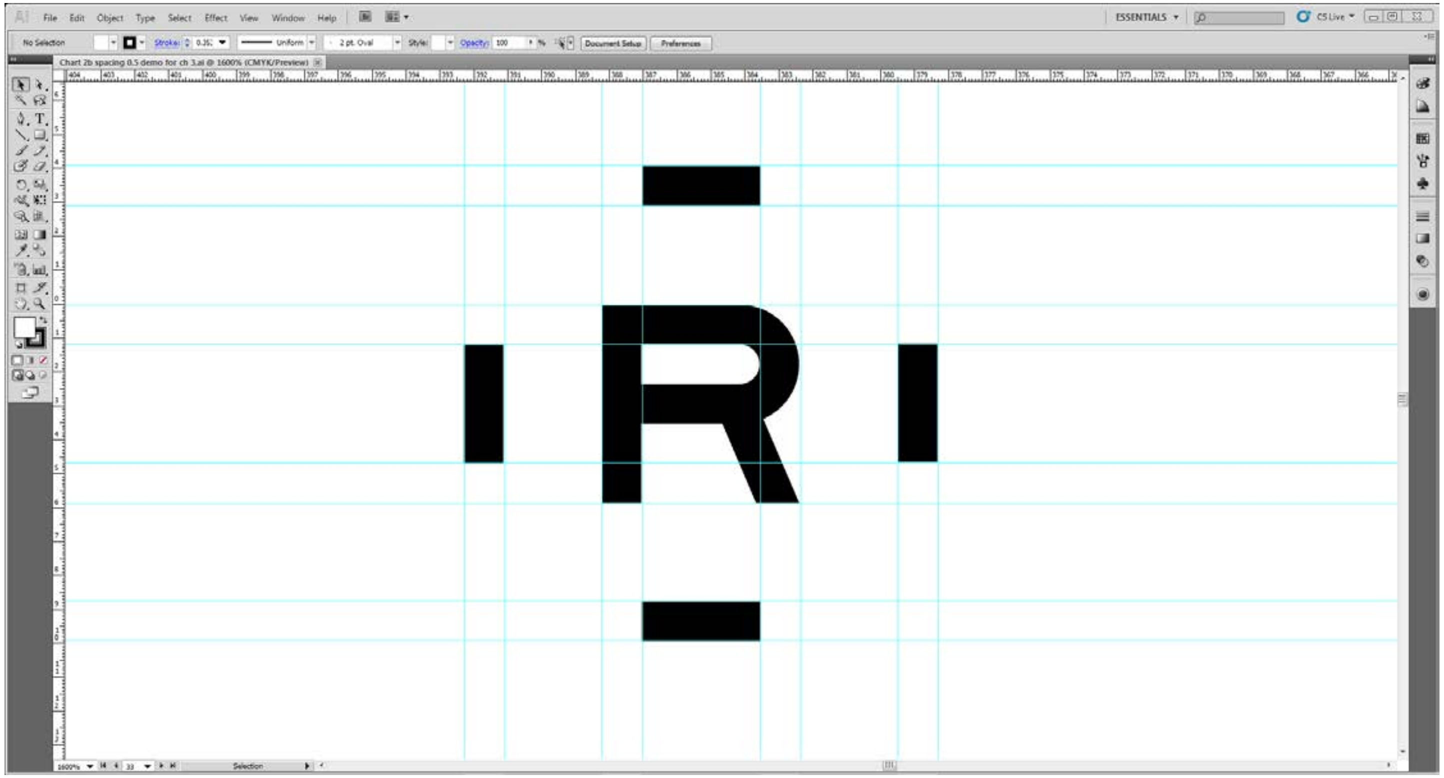


Figure 3.7 shows a screenshot of the Adobe Illustrator programme showing a Sloan letter ‘R’ with flaking bars placed half a letter-width from the edges of the letter. Blue lines are ‘guides’ which are not shown in the final display.

Having created the initial logMAR 0.0 display, 4 similar displays with different letters were produced and other sizes were created by magnification using an appropriate scaling factor. Other test configurations were created in the same way. A total of 8 tests were produced, unflanked letters plus the configurations shown in Figures 3.1, 3.2 and 3.3.

Initially, the tests were printed in booklet form, with spiral binding. However, pilot trials with 2 adult subjects indicated that the total testing time for the 8 tests would be too long and certainly too long for young children. Another presentation solution was sought whereby the tests could be presented more rapidly. The iPad (Apple inc. Cupertino, California) has been shown to be an appropriate platform for visual acuity testing, as long as glare can be eliminated (Black et al., 2013). Initial trials with 2 adults and 2 children of my experimental tests displayed on an iPad proved to be successful in reducing testing time. A testing distance of 4m was chosen to minimize any possible increase in acuity from shorter testing distance (Lippmann, 1971, Rozhkova et al., 2005). One researcher sat beside the participant, recording all responses, whilst another changed the iPad displays.

3.6 Crowding bars- pilot study

3.6.1 Background

Most, if not all, crowded visual acuity tests use flanking bars such that the dimensions of the bars are in proportion to the height and stroke width of the optotypes that they surround, typically the same height and single stroke width of the optotype (e.g. 5 stroke widths in length and 1 stroke width in width). It is not clear how this configuration arose; however, it is likely that the seminal work on contour interaction by Flom and colleagues (Flom et al., 1963b) was a significant influence. Nevertheless, such a configuration is almost ubiquitous in clinical studies using crowded visual acuity tests, for example, the surrounded HOTV letters in the Amblyopia Treatment Study (Holmes et al., 2001). An example of one of the optotypes used is shown in Figure 3.8.

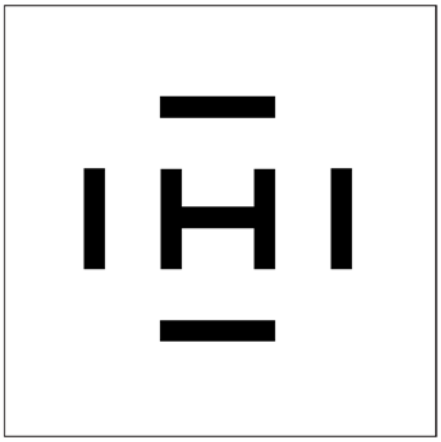


Figure 3.8 Appearance of a single surrounded HOTV letter from the Amblyopia Treatment Study, after Holmes et al. (2001).

What is notable is that while the edge-to-edge letter-to-flanker separation is held constant, the interaction influence of the vertical flanking bars may be different to the influence of the horizontal flanking bars simply because the extent of the interaction may depend on the relative ‘contact’ of the respective edges. In an early study of contour interaction, Takashi showed that foveal contour interaction is governed by the leading edge of the next nearest contour (Takahashi, 1968). Therefore in order to be assured that the average length of contour adjacent to the target letter was the same when we use letter or bar flankers, the length of the flanking bars was equated to the average length of the edges of the Sloan letters. The average length of the flanking edge from the Sloan letters was calculated and found to be 3 stroke widths. In Figure 3.9a, below, the nearest edge of the letter Y to the target letter C contributes one stroke width, the F, 5 stroke widths and so on. In Figure 3.9b, the C is surrounded by 4 bars, each 3 stroke widths in length. In this way, the length of contour near to the target letter was on average the same, regardless of whether the target letter was flanked by other letters or by bars of 3 stroke widths in length.

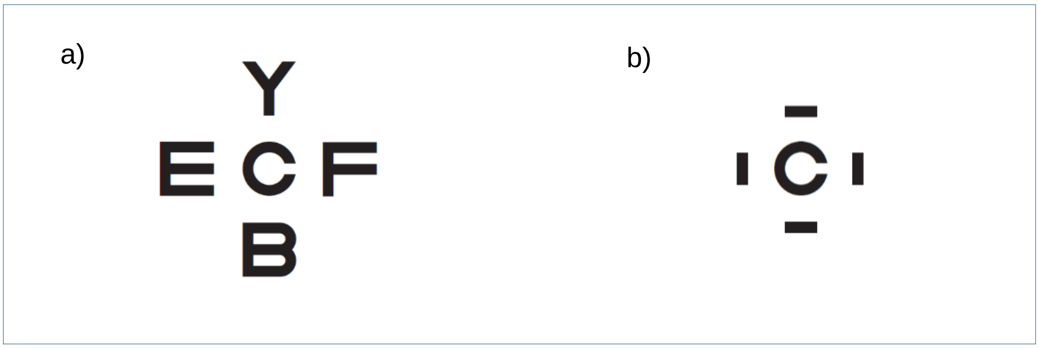


Figure 3.9 the letter C surrounded by 4 letters and 4 flanking bars of length 3 stroke widths.

Decreasing the size of the flanker would decrease its contrast energy (the product of the area and the squared contrast), so this may decrease the contour interaction (Pelli et al., 2004). Malania et al. (2007), in a Vernier alignment task with different lengths of flanking bars, showed strongest reduction in performance with flanking bars equal in length to the target bars, with both shorter and longer lines having less effect. In a peripheral vision crowding experiment using letters with bar flankers, Pelli et al found the size of the flanker had very little effect on the spatial extent of crowding (Pelli et al., 2004). However, in that study, the smallest flankers used were the same size as the target.

Figure 3.10 shows stimuli used by Leat et al. (1999) to measure contour interaction in foveal viewing. Significantly less crowding was found with the first configuration than with the others.

Leat et al. (1999) measured logMAR with the stimuli shown in Figure 3.10 in foveal viewing. When unflanked logMAR was subtracted from crowded logMAR with each of these stimuli, there was significantly less contour interaction from the ‘I’ distractors in the leftmost configuration than all the others, which were not significantly different to each other. This evidence infers a possible contribution for the amount of ‘edge’ closest to the target in determining the contour interaction, although the distance of the horizontally placed ‘I’ distractor from the target appears to be further away than the edge of the other distractors.

In view of the limited evidence as to the effect of reducing the size of the flanking bar next to a letter in foveal viewing, a pilot study was undertaken to ascertain if the depth of crowding was affected by reducing the length of the flanking bar.

Substitution theories of crowding (see Chapter 1) argue that in the integration phase of object recognition, flankers present in the zone of integration can be inappropriately integrated with the target features, causing a mis-perception of the object. If such a mechanism operated in the fovea, a short, dot flanker, the same size as the gap in the Landolt C, should more greatly reduce recognition than if the target was a Sloan letter. Therefore in addition to reducing the length of the flanking bars we also included a short ‘dot’ flanker condition to address this hypothesis.

3.6.2 Purpose

This pilot study had 2 specific aims:

i. to test whether a square 'dot' flanker results in more crowding for a Landolt C than a Sloan letter target
ii. to investigate the relative crowding resulting from differences in flanking bar lengths

3.6.3 Methods

Participants

Three adult observers with normal or corrected to normal visual acuity participated in the experiment. The research followed the tenets of the Declaration of Helsinki and approval of the experimental protocol was obtained from Anglia Ruskin University Research Ethics Committee. Informed consent was obtained before the experiments were conducted and after the nature and consequences of the study were explained.

Stimuli

Stimuli were generated on a PC monitor using a commercially available programme (Test Chart 2000Pro; Thomson Software Solutions, Herts, UK). The monitor was viewed through an optical quality mirror, resulting in a testing distance of 10.5m. The screen resolution was 1024 x 768 pixels (refreshed at 100 Hz) with a background luminance of 100 cd/m^2. Target stimuli were single flanked or unflanked black on white Landolt C optotypes or Sloan letters (including the letter C) presented at high contrast (-99% Weber). When present, the 4 flanking bars surrounding the optotypes were 1, 3 or 5 stroke widths in length and 1 stroke width wide, presented at the same polarity and contrast as the optotypes (Figure 3.11).

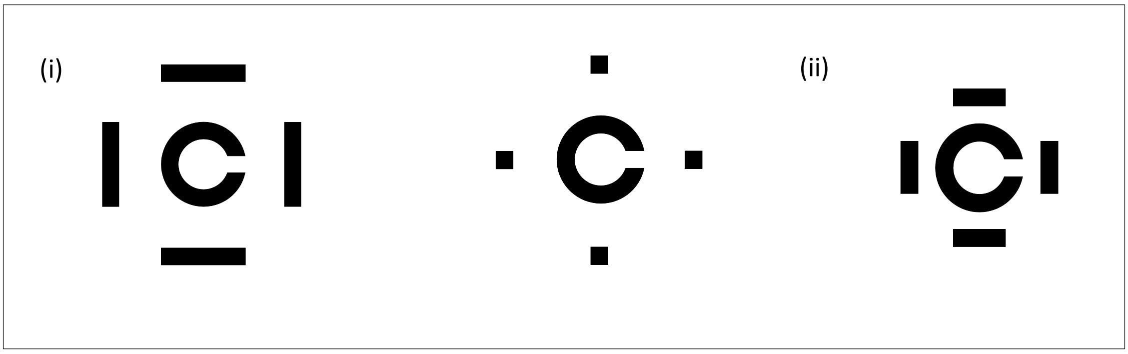


Figure 3.11 Example presentations of a C target with ‘dot’ and bar flankers, for the 2 conditions

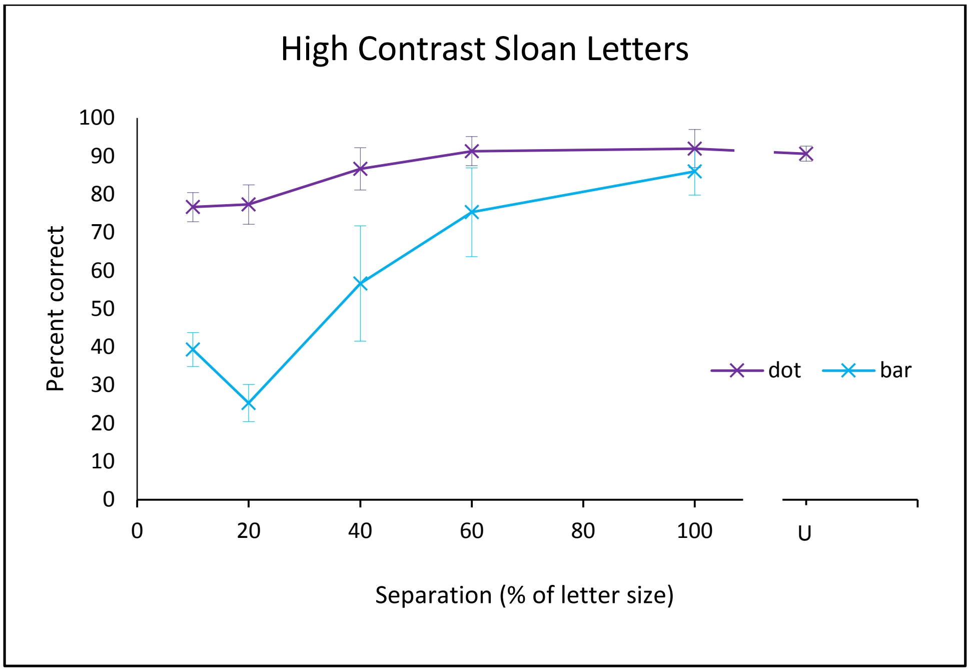
Procedures

Participants viewed the targets monocularly with appropriate spectacle lenses in place and were required to name the Sloan letter or the orientation of the Landolt C (up, down, left or right) depending on the condition being tested. The fellow eye was occluded. Participants were allowed unlimited viewing time. The percentage of correct responses was recorded for each run of 50 trials. For each participant, initial trials were carried out using unflanked optotypes (both Sloan and Landolt C) to find the size of optotype where performance was consistently between 80 and 95% correct. Data shown in the figures are the mean of runs of 50 trials averaged across participants.

In the first condition, (i), performance as a function of flanker stroke length (1 or 5 stroke widths in length) was investigated as a function of the edge-to-edge separation of flanker and optotype for each of the following separations: 10, 20, 40, 60, and 100% of optotype size. Displays with the 5 values of separation were presented randomly.

In the second condition (ii), performance as a function of flanker stroke length (3 stroke widths in length) was investigated for an edge-to-edge separation of flanker and optotype of 20%, where maximum reduction in performance from (i) occurred. This second condition was tested for 2 of the participants.

3.6.4 Results



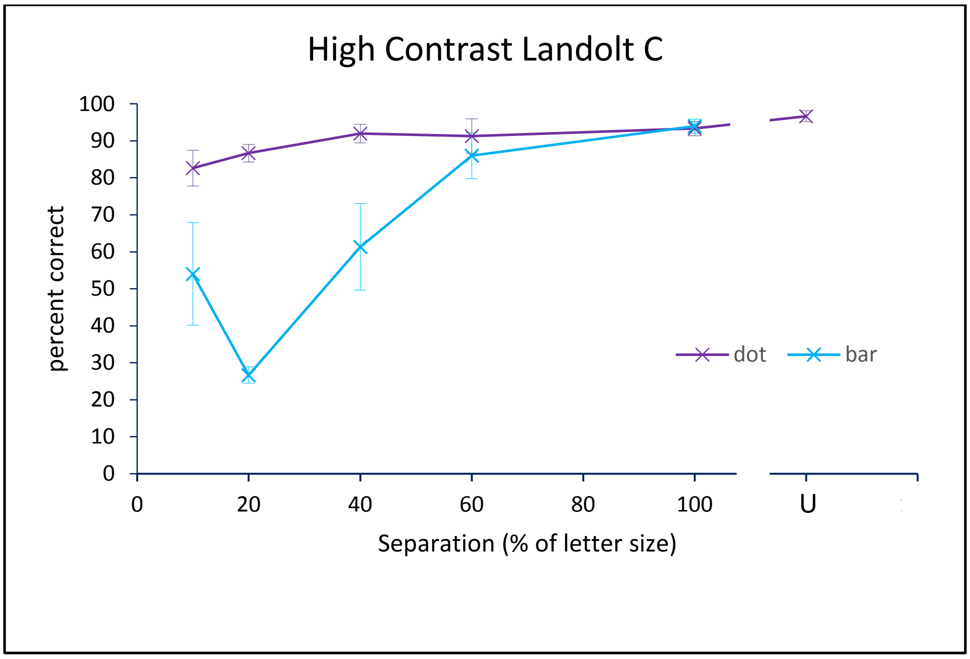


Figure 3.12 Percent correct responses as a function of edge-to-edge flanker-to-optotype separation, averaged across 3 participants, of Sloan letters (top panel) and Landolt C orientation (bottom panel) in the presence of dot (1 stroke width long) or bar (5 stroke widths long) flankers. U is unflanked. Error bars represent ±1 SE.

For both letter and Landolt C targets, the bar flanker had little or no effect on performance at flanker to optotype separations of one letter width (100%

separation) and greater. Closer separations of letter and bar caused progressively poorer recognition up to the maximum effect (25% correct) at a separation of 20%. Performance improved slightly when the bar was closer than 1 stroke width (Figure 3.12).

The presence of the 1 stroke width flanking ‘dot’ reduced performance for both targets to a much lesser extent than the 5 stroke width bar flanker. Performance was unimpaired with the flanking dot at a distance of 60% or greater. Closer separations reduced performance slightly, but unlike the longer flanking bar conditions, there was no improvement in performance at the closest separation (Figure 3.12).

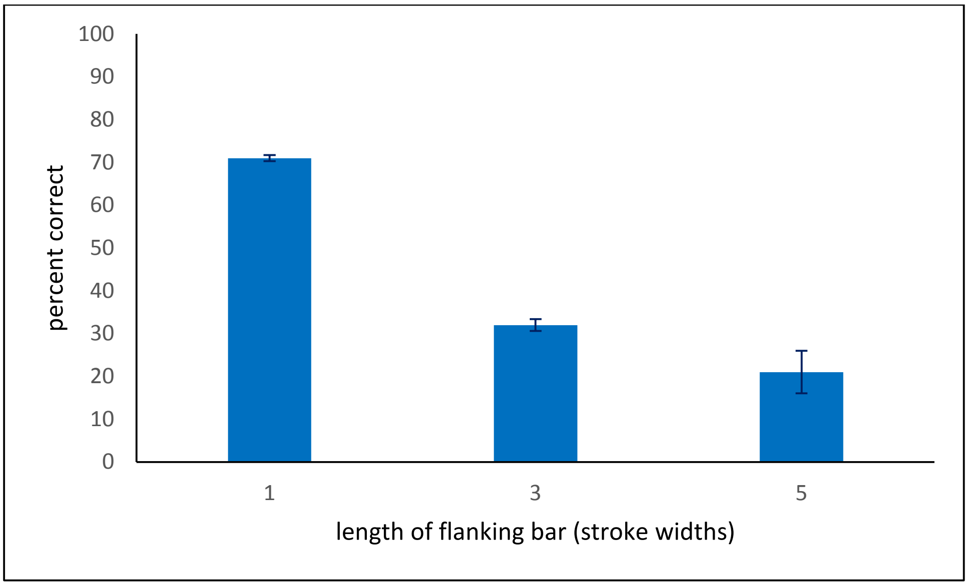


Figure 3.13 Percent correct performance, averaged across 2 participants, for Sloan letters flanked by bars of length 1, 3 and 5 stroke widths. Error bars represent ±1 SE.

Figure 3.13 shows the effect of length of flanking bar on letter recognition for bars of length 1, 3 and 5 stroke widths. The 5 stroke width flanking bar resulted in the most reduced performance and the 1 stroke width ‘dot’ impaired performance the least;

the 3 stroke width flanking bar fell between, but was closer to the 5 stroke widths bar.

3.6.5 Conclusions

In the first condition (i), percentage correct performance gradually reduced as the flanking bars were brought closer to the optotype, an effect consistent with previous reports describing contour interaction (Flom et al., 1963b). The position of the flanker which caused maximum interaction was similar to that found by Flom et al. (1963b). Both the magnitude and extent of contour interaction from the square ‘dot’ flanker on both targets was much less than the bar flanker. The effect of the ‘dot’ flanker on the Landolt C and Sloan letter targets was similar, so the hypothesis that the ‘dot’ may be substituted into the gap in the Landolt C was not proved for foveal viewing.

In pilot experiment (ii), the effect of flanker bars of length 5, 3 and 1 stroke width on the recognition of Sloan letters was investigated. The magnitude of contour interaction increased with length of the flanking bar, possibly reflecting the greater contrast energy or longer edge of the larger flankers.

Having demonstrated contour interaction with a bar of 3 stroke widths in length, it was decided to use flanking bars of this length in the experiments to follow.

Chapter 4

Foveal crowding differs in children and adults

4.1 Purpose

Chapter 1, section 1.8, reviewed evidence from the literature that aspects of foveal crowding in children differ from that in adults. Foveal crowding in children displays a larger critical spacing than in adults, which becomes adult-like possibly as late as the early teen years (Jeon et al., 2010, Semenov et al., 2000), target-flanker similarity may have an effect on foveal crowding in children that is not present in adult foveal viewing (Atkinson, 1991), and linear presentation of optotypes requiring multiple fixations may produce poorer visual acuity in young children than single, similarly crowded optotypes due to an increase in fixational instability, or relatively poorer saccadic accuracy (Aring et al., 2007).

The study described in Chapter 2 found that both spacing and type of optotype influenced crowding in children's visual acuity measurement and that the magnitude of crowding decreased between the ages of 4 and 10. Closer spaced optotypes induce more contour interaction, which adds to the overall crowding effect, and could explain the difference in measured vision between 2 letter tests with different spacing. But there could be a number of reasons why the Crowded Kay Picture Test induced less crowding than the letter tests. Part of the explanation may lie in the larger angular spacing of optotypes: nearby optotypes or the surround box may be further towards the outside of the zone of contour interaction than in letter tests of the equivalent acuity level, or fewer fixation errors may be made by a child naming more widely spaced optotypes in linear format. An alternative explanation could involve attentional factors such as target-flanker similarity.

Chapter 3 described the development of custom-designed tests to allow crowding features to be varied independently. The aim of this chapter is to describe a study which uses these tests to determine the effects of foveal crowding on visual acuity in normally sighted children at various ages as a function of target-flanker separation, single versus linear presentation of optotypes and target-flanker similarity.

The research questions are:

3. What is the effect of spacing between a flanking bar and target letter on acuity in children and adults?
4. What are the relative contributions of contour interaction, gaze control and attention on crowded acuity in children and adults?
5. Can mis-naming errors point to any differences between reading behaviour of line charts in children and adults?

4.2 Methods

4.2.1 Participants

Seventy five children were recruited from a local primary school in Cambridge, UK, and a control group of 27 adults was recruited from the local community. Written, informed consent was obtained from the children's parents or guardians and from the adult participants and verbal assent from the children, after all the procedures were explained to them. Ethical approval for the study was obtained from the University Research Ethics Panel and the study followed the tenets of the

Declaration of Helsinki. All participants were screened and excluded from the study if any one of the following criteria were met: visual acuity worse than 6/9 Snellen chart; significant hyperopia, defined as visual acuity of 6/12 or better when viewing through a +2.00D lens; presence of strabismus on cover test or no stereopsis measured on the Lang II Stereotest (Lang-Stereotest, Küsnacht, Switzerland), and an inability to co-operate with the experimental protocol. Four children who failed the screening were referred to an optometrist for a full eye examination and 4 other children did not complete all of the tests. None of these children were included in the study. A further 5 children were not available on the test days. Therefore data from a total of 62 children were used in the study.

For analysis, participants were grouped into 3 age bands, 4-6 years (32 participants, mean age 5yrs, 9 months), 7-9 years (30 participants, mean age 8 yrs, 7 months) and adults over 18 years (27 participants, mean age 25 yrs, 0 months). The number of participants in each group was sufficient to obtain a power of 80% at the 5% level (two tailed) for an effect size of 0.1 logMAR.

4.2.2 Tests

A series of letter tests was produced comprising single letters and lines of letters, with bar and letter flankers to create a number of conditions where the influence of contour interaction, eye movements and attention could be inferred (Table 4.1). The tests used the Sloan letter set, constructed in a 5x5 format, with the height and the width of each letter 5 times the stroke width. Individual relative legibility of each Sloan letter differs by no more than 12% from the mean relative legibility of the set (Sloan et al., 1952). The tests were produced using Adobe Illustrator CS5 (Adobe Systems Incorporated). Non-Sloan letters, except the letter **I**, were used as flanking letters and were constructed in the same way using the same software (Pelli et al., 1988). Sloan letters were not used as flankers in order that naming of the flanking letters was not an option in the 10AFC task. In the case of a flanking letter being named in error, the examiner directed the participant back to the target letters. In a later experiment, it was decided to use Sloan letter flankers as an additional condition, so that naming a letter above or below the intended letter (vertical errors) could be analysed.

Tests were displayed, black letters on a white background, on an iPad 2 (Apple Inc. Cupertino, California) with a resolution of 1024-by-768 at 132 pixels per inch, so 1 pixel subtended 0.17' of arc at a test distance of 4m. The iPad's auto-brightness function was disabled and the brightness set to maximum. Background luminance of the display was 310 cd/m^2, resulting in a letter Weber contrast of -99%.

The acuity range of the tests was logMAR 0.4 to logMAR -0.4 in steps of 0.05 logMAR and for each level of acuity, 5 letters were scored on each test. In the single letter presentations, 5 different letters of the same size were shown consecutively. Each set of 5 letters was selected to have a similar combined relative legibility of 4.8 or 4.9 (Strong and Woo, 1985). Tests were constructed with edge-to-edge separations between flankers and optotypes ranging from 0.25 to 1.5 letter widths and including an unflanked condition (Table 4.1). The length of the bar flankers was 0.6 times letter height, or 3 stroke widths, based on maintaining a constant average length of flanking edge nearest to the target. A bar of this length was shown in Chapter 3 to impair the recognition of a letter target slightly less than a bar of 5 stroke widths height. The line tests were constructed so that letters broadly composed of straight lines (e.g. H, N, V, K, Z) alternated with round shaped letters (O, D, C, S, R).

Table 4.1 Tests used in the study. Letters were presented in single (S) or linear (L) format with bar (B) or character (C) flankers. The edge-to-edge separation measured as a proportion of letter size is denoted by the subscript. The red line at the left edge of the linear chart denotes the side from which reading should begin.

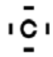
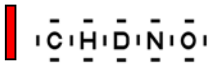
Test	Letter target	Flanker type	Flanker spacing	Example display
S_0	single	no flanks		
$SB_{0.25}$	single	bars	0.25	
$SB_{0.5}$	single	bars	0.5	
$SB_{1.0}$	single	bars	1.0	
$SB_{1.5}$	single	bars	1.5	
$LB_{0.5}$	linear	bars	0.5	
$SC_{0.5}$	single	characters	0.5	
$LC_{0.5}$	linear	characters	0.5	

Table 4.1 shows the tests used in the study, with an example presentation of each. Baseline data using test S_0 (unflanked logMAR), were used to normalise subsequent results to minimise any potential confound between letter size and inter-letter spacing for different acuity sizes (Levi, 2008).

The following between test comparisons were made:

1. $SB_{0.25}$, $SB_{0.5}$, $SB_{1.0}$ and $SB_{1.5}$ to determine the magnitude and extent of contour interaction

2. $SB_{0.5}$ with $LB_{0.5}$ and $SC_{0.5}$ with $LC_{0.5}$, to determine the effect of linear presentation, with controlled contour interaction

3. $SB_{0.5}$ with $SC_{0.5}$ and $LB_{0.5}$ with $LC_{0.5}$ to determine the effect of letter rather than bar flankers (increased attention demand), with controlled contour interaction

In $LB_{0.5}$, the bar flanker in between letters was retained so that the next nearest contour to each letter would always be a bar at 0.5 letter widths separation from the target letter, as in $SB_{0.5}$.

4.2.3 Procedure

Children were tested in a school classroom with lighting adequate for visual acuity testing (National Academy of Sciences-National Research Council Committee on Vision,1980), approximately 100 lux. The experimental tests were viewed by the right eye of eligible participants and spectacles were worn if habitually used. Participants sat 4m from the iPad, which was mounted on a tripod stand directly in front of them in a position where reflections from the screen were not evident (Black et al., 2013). Participants held a card showing the ten Sloan letters. Where children were unable to name a letter, they pointed to it on the card. The 8 experimental tests, S_0, $SB_{0.25}$, $SB_{0.5}$, $SB_{1.0}$, $SB_{1.5}$ $LB_{0.5}$, $SC_{0.5}$ and $LC_{0.5}$ were shown in a random order, different for different individuals. Participants were allowed unlimited viewing time. Testing began using a letter size 0.1 logMAR larger than the acuity found from initial screening. Smaller letter sizes were presented in steps of 0.05 logMAR until the termination point was reached, at which 3 or more letters of one size were named incorrectly. If any letters at the starting level were named incorrectly, the next largest size was presented until a size was found where all 5 responses were correct. When a participant was not sure of a letter, they were encouraged once to guess. For the single letter test with letter flankers, $SC_{0.5}$, participants were asked to read the middle letter only. For the line test with letter flankers, $LC_{0.5}$, participants were asked to read all the letters on the middle row but only the central 5 letters were scored. A red line on the left hand side of the two line tests $LB_{0.5}$ and $LC_{0.5}$ indicated the side where reading should commence. Pointing at the letters by the examiner was not used under any test condition.

All responses were recorded on a spreadsheet by the examiner and letter-by-letter scoring was used, such that a missed letter at any acuity level resulted in an increase to the score of 0.01 logMAR. For the line tests, $LB_{0.5}$ and $LC_{0.5}$, if a participant read the incorrect number of letters in a line, without indicating that they were leaving one out, the responses were recorded in the order and position they were read. The procedure for testing the adults was the same as for children except testing was carried out in our laboratory with equivalent illumination. For comparison adult participants also had their visual acuity measured using an internally illuminated ETDRS chart (Precision Vision Inc, La Salle, IL) (Ferris et al., 1982).

4.2.4 Data Analysis

Data were analysed using a repeated measures ANOVA with a Greenhouse-Geisser correction for violation of sphericity applied, when necessary (Keppel, 1982). Post-hoc analyses with Tukey HSD correction were also performed as required (Statistica StatSoft, Ltd, Tulsa). Letter naming errors were also analysed in the two line tests, $LB_{0.5}$ and $LC_{0.5}$ to investigate any difference in pattern between the age groups and tests. Errors were defined as either 'adjacent' if the response letter was adjacent horizontally to the target letter (either left or right), or 'random' if any other letter was named. In the line test with bar flankers, $LB_{0.5}$, errors pertaining to just the central 3 letters were analysed, as the end letters only had one possible adjacent option. In the line test with letter flankers, $LC_{0.5}$, errors pertaining to the central 5 letters were analysed. Two analyses were carried out. The first one looked for a difference in proportion of adjacent and random errors between the two line tests and the second looked for a difference in the proportion of right and left errors. Chi square tests were performed to assess statistical significance.

4.3 Results

Mean unflanked acuity was better than 6/6 (logMAR 0.0) in all 3 age groups (Figure 4.1). There was no significant difference in acuity in the adults between the ETDRS chart and our single letter test with bars at one letter-width from the target ($SB_{1.0}$), p=0.66, indicating that potential reflections from the iPad did not interfere with the acuity measurements (Black et al., 2013). Mean unflanked logMAR was 0.07 worse in the younger children (4-6yrs) than in the older children (7-9 yrs) ($p<0.05$) and 0.1 worse in the younger children than the adults ($p<0.01$).

4.3.1 Extent of foveal contour interaction

Figure 4.1 plots logMAR using the single letter flanked tests ($SB_{0.25\text{-}1.5}$) as a function of letter and flanker separation for the younger children (diamonds and dotted line); older children (squares and dashed line) and adults (triangles and solid line). For each of the age groups, maximum contour interaction occurs at the nearest letter-flanker separation (0.25 letter widths). For all groups, and consistent with previous results, (Jeon et al., 2010, Semenov et al., 2000, Fern and Manny, 1986, Manny et al., 1987), logMAR improves as letter-flanker separation increases.

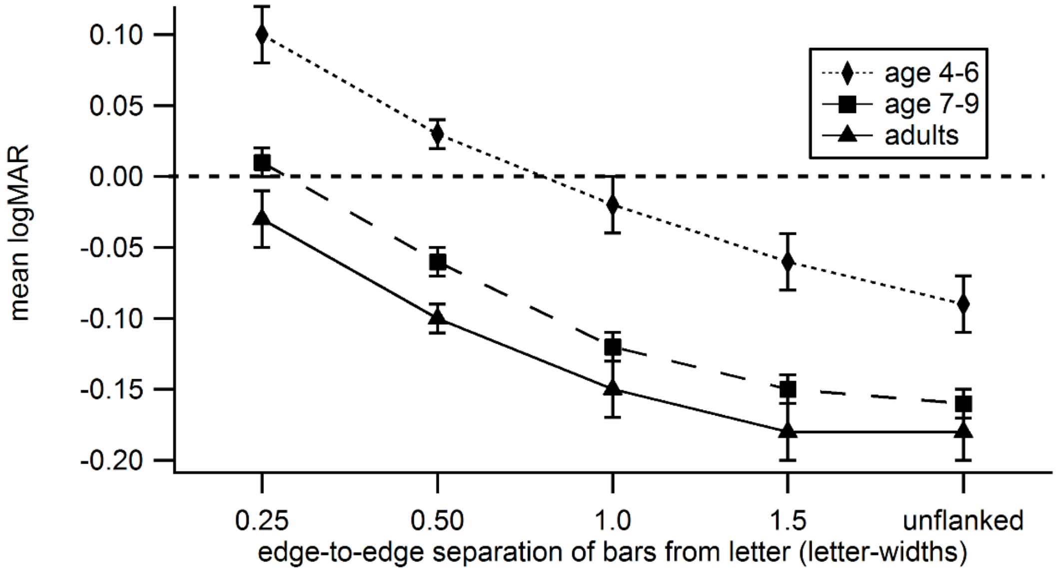


Figure 4.1 shows logMAR plotted as a function of target and flanker separation for the single letter flanked tests for the 3 age groups; younger children (4-6 yrs): diamond symbols, dotted line; older children (7-9 yrs): square symbols, dashed line and adults: triangle symbols, solid line. The horizontal dotted line shows logMAR 0, or 6/6. Error bars represent ±1 SE.

A separate one-way ANOVA (repeated measures) comparing logMAR as a function of letter-flanker separation was performed for each age group and showed a significant effect of separation in each: 4-6 yrs $F(4,124)=84.7$, $p<0.001$; 7-9 yrs $F(4,120)=96.2$, $p<0.001$, adults $F(4,104)=73.1$, $p<0.001$. Post-hoc testing (Tukey test) showed that unflanked logMAR was not significantly different to the widest letter-flanker separation of 1.5 in both groups of children: 4-6 yrs $p=0.066$, 7-9 year olds $p=0.668$, indicating no contour interaction at this separation. For all other letter-flanker separations, contour interaction was evident as the logMAR was significantly greater than the unflanked condition (4-6 year olds $p<0.001$, 7-9 year olds $p=0.001$).

In contrast, the adults' results showed that unflanked logMAR was not significantly different to the flanked conditions for the 1.5 (p=1.0) and 1.0 letter-flanker (p=0.096) conditions, consistent with previous results of the extent of foveal contour interaction in adults (Simmers et al., 1999, Flom et al., 1963b). This shows the extent of contour interaction to be less in adults than in children.

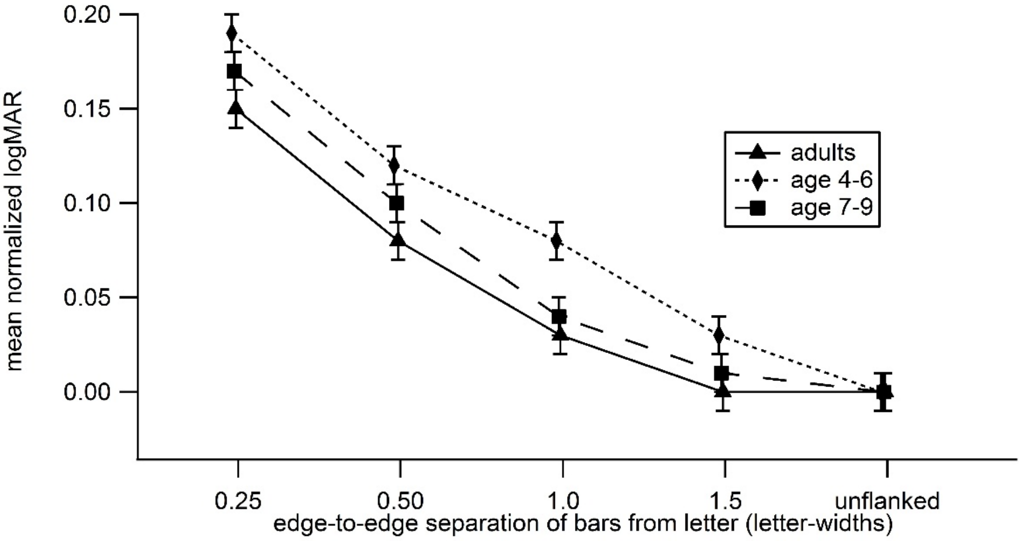


Figure 4.2 shows mean, normalized logMAR plotted as a function of target and flanker separation for the single letter flanked tests for the 3 age groups; younger children (4-6 yrs): diamond symbols, dotted line; older children (7-9 yrs): square symbols, dashed line and adults: triangle symbols, solid line. Error bars represent ±1 SE.

The data from the single letter tests with bar flankers ($SB_{0.25\text{-}1.5}$) were normalized to the uncrowded condition S_0 (Figure 4.2). On average, the depth of crowding for the single letter, bar surround condition was significantly greater in the younger children (4-6 yrs) than in the adults (p<0.05). There was no significant difference between the depth of crowding on average between either the older children and the younger children (*p*=0.3) or the older children and the adults (*p*=0.5).

4.3.2 Effect of flanker type and single versus linear letter targets

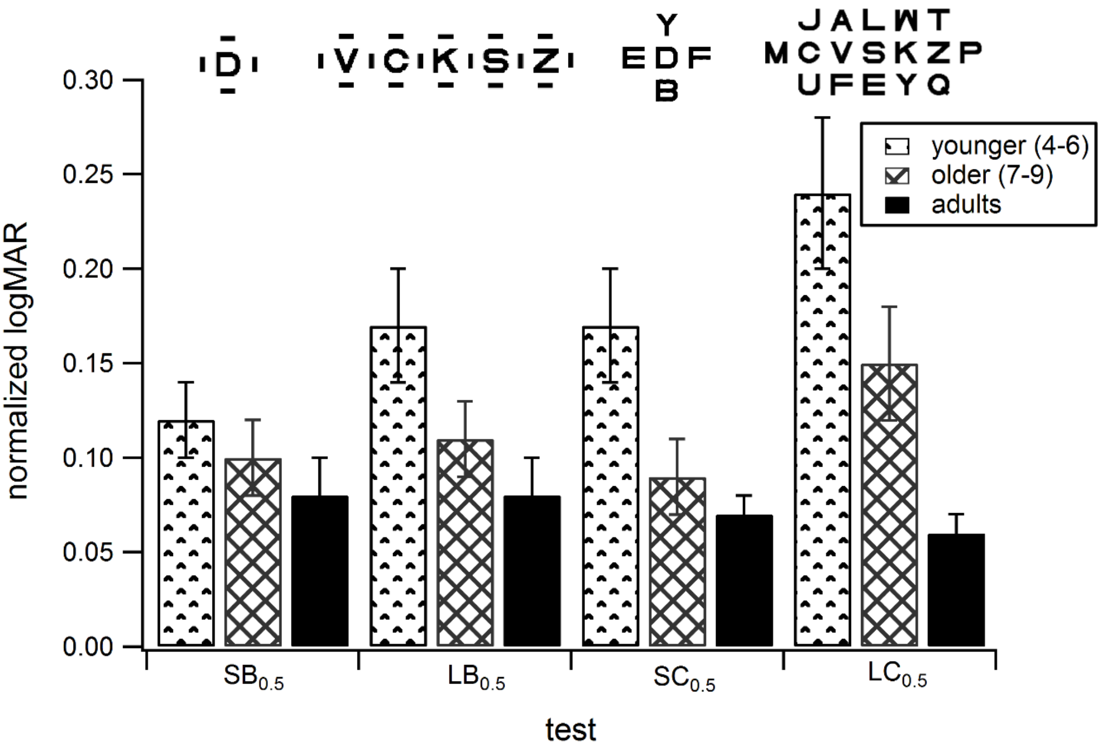


Figure 4.3 shows mean logMAR for each group, normalized to the unflanked acuity, for the four crowding conditions: single letter with bar or letter flankers and line of letters with line or letter flankers. Dotted bars show younger children (4-6 yrs), cross-hatched bars show older children (7-9 yrs), and solid bars show adults. Edge-to-edge target-flanker separation was 0.5 letter-widths. Error bars represent ±1 SE.

A 3 (age) by 4 (tests) ANOVA (repeated measures) yielded a significant main effect of age F(2,87)=18 (*p*<0.001), a significant main effect of test F(2.76, 240.6)= 22.38 (*p*<0.001), and a significant interaction between age and test F(5.53,240.6)=13, *p*<0.001. Crowding varied across tests in the two groups of children, but not in the adults, for whom there was no significant difference in logMAR across the tests.

Further analysis of the interaction showed that similar to the adult group, the group of older children (7-9 yrs) showed no significant difference in logMAR between the single letter tests with bar or letter flankers, $SB_{0.5}$ or $SC_{0.5}$ or the line of letters with bar flankers, $LB_{0.5}$. However, a significant difference in logMAR was found for the most complex test, the line test with letter flankers, $LC_{0.5}$ ($p<0.001$), with acuity around 0.05 logMAR poorer in this test than in the other 3 tests.

The younger children (4-6 yrs), in the single letter condition, showed more crowding (0.05 logMAR) with letter flankers ($SC_{0.5}$) than bar flankers ($SB_{0.5}$), $p<0.001$. They also showed more crowding (0.05 logMAR) in the linear test with bar flankers ($LB_{0.5}$) than in the single letter test with bar flankers ($SB_{0.5}$), $p=0.003$. These results show that using letter rather than bar flankers and using a linear rather than single optotype presentation both present a similar level of increased crowding for the younger children. In addition, for the linear test with letter flankers ($LC_{0.5}$), there is a further increased level of crowding, resulting in a mean worsening of visual acuity of 0.12 logMAR compared to the single letter with bar flankers ($SB_{0.5}$), $p<0.001$.

4.3.3 Error analysis

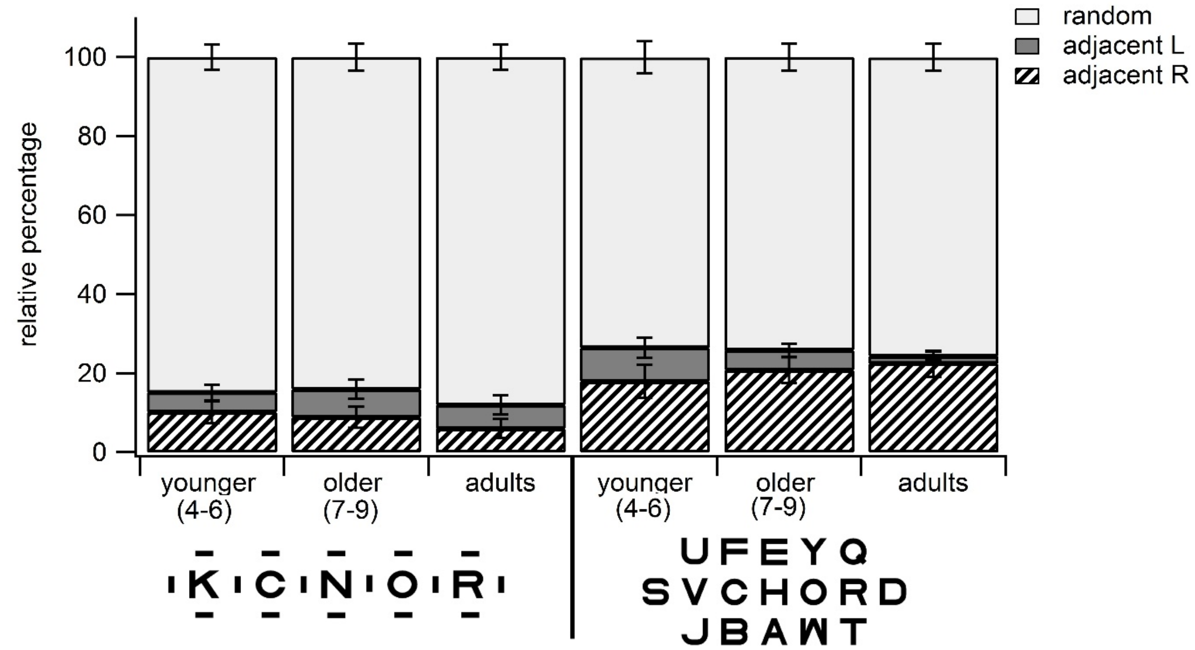


Figure 4.4 shows the relative percentages of the different error types in the line tests, LB0.5 and LC0.5 for the three age groups. Light grey shading shows random errors, dark shading shows adjacent left errors and diagonally striped shading shows adjacent right errors. Error bars represent ±1 SE.

Figure 4.4 shows the relative percentages of the different error types in the line tests $LB_{0.5}$ and $LC_{0.5}$ for the three age groups. Light grey shading shows random errors, dark shading shows adjacent left errors and diagonally striped shading shows adjacent right errors.

Two error analyses were conducted comparing $LB_{0.5}$ and $LC_{0.5}$. As expected, most of the errors made were random errors. The first analysis compared the proportion of adjacent and random errors between the two line tests. On average, more adjacent errors were made in the test with letter flankers ($LC_{0.5}$), compared to the test with bar flankers ($LB_{0.5}$), (χ^2=14.0, p<0.001).

The second analysis examined the frequency of right and left adjacent errors in the line tests. In the line test with bar flankers, $LB_{0.5}$, the numbers of right and left errors were not different (χ^2=2.22, *p*=0.329). However, when letter flankers were used ($LC_{0.5}$), there were more right than left errors in each age group and the proportion of right: left increased with age (χ^2=46.09, *p* <0.001).

4.4 Discussion

4.4.1 Summary of results

We used a series of custom designed visual acuity tests to infer the relative influence of target-flanker distance, linear versus single presentation and target-flanker similarity on visual acuity (logMAR) in children and adults. Unflanked acuity was on average, better than logMAR 0.0 (6/6) in each of the 3 groups although a developmental trend was evident. Averaged unflanked acuity was worse in the 4-6 year old group than in the 7-9 year olds and adults, consistent with reports that have showed maturation of unflanked acuity between 4 and 6 years of age (Leat et al., 2009, Simons, 1983). The slightly poorer acuity in the youngest age group may reflect continuing development of the retinal mosaic (Yuodelis and Hendrickson, 1986). In our study reported in Chapter 2 (Norgett and Siderov, 2011), we found no change in unflanked acuity in a different sample of children, but over the same age range, which may reflect a sampling issue in the age bands used, or the greater variance in the 7-9 year olds in our previous study as a result of different inclusion criteria.

4.4.2 Extent of contour interaction

Consistent with previous reports (Semenov et al., 2000, Jeon et al., 2010, Bondarko and Semenov, 2005), contour interaction was greater in extent in both groups of children than in the adults. On average, our results suggest that the age at which the critical spacing becomes adult-like is at least beyond 9 years. Although retinal changes are potentially ongoing in the younger children (Yuodelis and Hendrickson, 1986, Simons, 1983), the larger zone of contour interaction we observed in both groups of children probably reflects underlying cortical rather than retinal development, as crowding is known to reflect cortical processes (Flom et al., 1963a, Pelli, 2008). Kozma showed that integration of contours is probably mediated by long-range neuronal connections and that visual spatial integration is still developing between 5 and 14 years of age (Kozma et al., 2001). In addition, Huttenlocher et al. (1982) showed changes in synaptic density in the cortex which continued until around 11 years. Such results support the notion of ongoing visual maturation contributing to the development of crowding.

4.4.3 Magnitude of contour interaction

In the normalized single letter bar surround condition ($SB_{0.5-1.5}$), we found the depth (or magnitude) of contour interaction, on average, to be larger in the children than the adults (see Figure 4.2). This difference, albeit small, was significant between the youngest children (4-6 yrs) and the adults, showing recognition of letters in the presence of flanking bars at a particular distance to be impaired more in young children than in adults. Similar to section 4.4.2, this finding infers that the mechanism governing contour interaction is not fully mature in younger children- that some tuning of inhibitory interaction zones, or focussing of spatial attention is still taking place.

4.4.4 Effect of Attention

Our findings support the view that in young children, crowded visual acuity is determined not only by the resolution potential of the eye and by the distance of nearby objects to the target, but also by the attention demand in disregarding the nearby objects in favour of the target.

Comparing single letters flanked by letters, ($SC_{0.5}$), to single letters flanked by bars, ($SB_{0.5}$), observers were required to preferentially process the target letter whilst ignoring the flanking letters; the young children (4-6 yrs) had more difficulty ignoring the letter flankers than bar flankers at the same distance from the target ($SB_{0.5}$), resulting in a logMAR reduction of 0.05, or half a line of letters. The letter flankers were categorically similar to the target, so selecting the target letter and ignoring the flanking letters represents a greater demand on attention than naming a letter with bar flankers. This stronger crowding where there is more similarity of the target and flankers is consistent with the results of Atkinson (1991), and is similar to findings in the adult periphery (Leat et al., 1999, Kooi et al., 1994, Zhang et al., 2009, Nazir, 1992, Bernard and Chung, 2011), but not in adult foveal viewing (Leat et al., 1999, Atkinson, 1991, Song et al., 2014).

Theories of visual attention propose competition for processing of information in the visual system where there is limited capacity, a 'bottom up' mechanism, coupled with a 'top-down' selection of the target (Desimone and Duncan, 1995). Studies which explore the development of visual attention show children to be less efficient at allocating attentional resources than adults rendering them less able to ignore task irrelevant stimuli (Enns and Akhtar, 1989, Pastò and Burack, 1997).

A recent study using a tracking paradigm with a target and distractors at varying distances showed that young children were able to process relevant information in the presence of competing stimuli as effectively as adults, until the separation of target and nearby objects became small (Wolf and Pfeiffer, 2014). It was shown that the spatial extent of this 'attentional focus' decreased significantly between 7 and 9 years, but was not yet mature at 13 years.

4.4.5 Letter strings- effect of eye movements

These results show that in the youngest children (4-6 yrs), recognising a string of 5 letters with surrounding bar contours ($LB_{0.5}$) is harder than similarly flanked single letters ($SB_{0.5}$), resulting in a logMAR reduction of 0.05, or half a line of letters. At this age, children are learning to read, but are not sufficiently practised to have reached their maximum reading speeds (Curtis, 1980, Aghababian and Nazir, 2000), so development of line acuity could be linked to learned patterns of reading. Unpractised readers could make less accurate saccades, or poor fixation could lead to loss of positional information. Beginning readers have also been shown to make more 'regressions' or re-fixations when reading (Rayner and Duffy, 1986). This behaviour could contribute to the younger children losing their place when reading along the line tests in our study. Even in adults, Popple and Levi (2005) showed that compared to widely spaced letters, crowded letters lead not only to recognition errors, but also to loss of position information in the periphery. A similar mechanism may operate to a lesser extent in foveal viewing in children. Furthermore, looking at a line of letters rather than a single, flanked letter represents more information in the respective cortical receptive field, so poorer performance in children may also be as a result of divided visual attention.

In older children (7-9 yrs), neither linear presentation nor increased letter-flanker similarity alone was sufficient to make mean, normalized logMAR different from adults. However, in the linear test with letter flankers, $LC_{0.5}$, the resulting increased crowding caused logMAR for this test to be significantly poorer than the mean adult logMAR. We suggest that, reading along the line of letters, the letter flankers caused more difficulty than the bar flankers in children because of the requirement for accurate eye movements and the increased attention demand, described above.

It is difficult to separate visual attention and eye movements as they are very closely linked (Flom, 1991, Hoffman and Subramaniam, 1995). Nevertheless, our analysis of errors made when reporting the letters, showed that when bar flankers are used, the resulting naming errors have a similar pattern across the age groups causing a combination of common letter confusions, and random guessing. However, when letter flankers are used, more adjacent errors occurred, suggesting that participants were at times losing their place as they read the line of letters. Furthermore, the way in which participants lost their place in the line changed with age. In adults, the majority of the adjacent errors were 'right' errors, caused presumably by omitting a letter on reading from left to right. In the younger children, although there were more 'right' than 'left' errors, the proportion of right: left errors was lower, suggesting that the younger children were also getting lost on reading the line, but as well as missing letters they also made re-fixations in the right to left, or backwards direction. We infer that this is evidence in support of an immature control of gaze in the younger children, as previously suggested (Kothe and Regan, 1990). Although the nearest contour to the letter being read was the same in both line tests ($LB_{0.5}$ and $LC_{0.5}$), the centre-to-centre separation of letters was less in the test with letter flankers ($LC_{0.5}$), putting a greater demand on accurate fixation of the letters near threshold. Of the two differences in the line tests: the inter-letter separation and the flanker type (letter or bar), we consider the flanker type to be the more significant. The difference in logMAR between $SC_{0.5}$ and $SB_{0.5}$ - using letter rather than bar flankers found in the single letter condition (0.05 logMAR) accounts for most of the difference observed between the 2 linear tests, $LC_{0.5}$ and $LB_{0.5}$ (0.07 logMAR).

An alternative explanation for errors in the line tests could be that the participants became muddled in the stage of rehearsing the letters mentally after visualizing them and before speaking them. We do not consider this explanation to be the primary cause of errors, as participants were given unlimited time to read the lines of letters and there was no requirement to look at all five letters before naming them.

The ability to subitize, or know the number of objects in an array without counting them, increases throughout childhood (Halberda and Feigenson, 2008). This may be linked to a child's ability to accurately read longer strings of letters; a child may struggle to find their place if they are unsure how many letters are in the line they are reading. In the linear test with letter flankers ($LC_{0.5}$), seven letters were read, whilst in the linear test with bar flankers ($LB_{0.5}$), only 5 letters were read. This difference gives more opportunity for placement errors in the 7 letter test.

4.4.6 Conclusions

These results show a greater extent of contour interaction in children than adults, which is still not mature by 9 years of age. Two other factors are also likely to contribute to the overall crowding effect in children younger than 7: the greater attention demand of increased letter-flanker similarity and the more precise eye movement control required to read a string of letters. The data suggest that both attention and eye movement factors mature individually by around 7 years of age, but can have a cumulative effect which extends beyond age 7. These results have implications for the design and use of visual acuity tests for screening of vision in young children.

Chapter 5

Effect of crowding on the slope of the psychometric function

5.1 Purpose

The repeatability of a visual acuity test will describe its ability to detect a change in visual acuity between measurements, a metric important to detecting ocular pathology, monitoring the success of interventions, monitoring visual development and in determining the number of subjects needed in clinical trials in eye care (Hazel and Elliott, 2002, Reeves et al., 1987, Gordon et al., 1998). The repeatability of visual acuity measurements is influenced by a number of factors including relative legibility of optotypes, test chart design, scale increment and scoring criteria and may be expected to be greater where there is a smaller confidence interval for the obtained threshold e.g. where more letters are used to define the threshold. (Bailey et al., 1991, Raasch et al., 1998, Carkeet, 2001). Letter-by-letter scoring with a smaller scale-increment increases a test's sensitivity to reliably detect smaller degrees of change (Bailey et al., 1991). Furthermore, repeatability has been found to decrease in the presence of optical blur (Rosser et al., 2004, Carkeet et al., 2001).

Repeatability of a visual acuity test is often described by the 95% confidence limits of the test-retest variability, TRV (Rosser et al., 2004). This is the range of acuity in which there is 95% certainty that 2 measurements made from the same individual in the absence of any change will lie. The TRV is calculated as 1.96 x the standard deviation of the difference between test and retest data (Rosser et al., 2004, Bland and Altman, 1986).

Table 5.1 summarizes studies which report 95% ranges of TRV for the ETDRS chart, Bailey-Lovie, or similar charts. There are a number of methodological variations between studies which have been proposed to explain the variability in TRV range, including the length of time between repeated measures, use of multiple examiners, the presence of ocular pathology, amblyopia or uncorrected refractive error and number and age of participants (Rosser et al., 2003, Reeves et al., 1993).

Table 5.1 shows previous published ranges for 95% test-retest variation (TRV) with the ETDRS or Bailey-Lovie charts. Unless otherwise stated, best corrected VA was measured.

Study	**Chart**	**Participants**	**TRV (logMAR)**
Arditi and Cagenello (1993)	ETDRS	Adults with normal vision	±0.09
Bailey et al. (1991)	ETDRS	Adults with normal vision	±0.10
Beck et al. (2003)	ETDRS	Children and adults with normal vision and pathology	±0.14
Laidlaw et al. (2008)	ETDRS	Adults with normal vision and pathology	±0.12
		Amblyopic children	±0.12
Manny et al. (2003)	ETDRS	Children with normal vision	±0.15

Rosser et al. (2001)	ETDRS	Adults with pathology	±0.18
Rosser et al. (2003)	ETDRS	Adults with normal vision	±0.11
Vanden Bosch and Wall (1997)	ETDRS	Adults with pathology	±0.07
Hazel and Elliott (2002)	ETDRS	Adults with normal vision	±0.14
	Bailey-Lovie		±0.12
Lovie-Kitchin (1988)	Bailey-Lovie	Children and adults with normal vision	±0.16
Reeves et al. (1993)	Bailey-Lovie	Adults with normal or moderately reduced vision	±0.19
Kheterpal et al. (1996)	LogMAR chart	Children with reduced vision uncorrected RE LE	±0.21 ±0.25
Siderov and Tiu (1999)	LogMAR chart	Adults normal vision, corrected and uncorrected vision	±0.15
Elliott and Sheridan (1988)	Ferris logMAR	Adults with normal vision	±0.07
		Adults with cataract	±0.09

The highest TRV range in Table 5.1 is from the study of Kheterpal et al. (1996), where the participants were children with reduced vision, whose visual acuity was measured without correction. Despite the findings of that study, the evidence of others does not support a general assertion that children's visual acuity measurements are less repeatable than adults (Manny et al., 2003, Beck et al., 2003, Laidlaw et al., 2008).

Some of the lower TRV ranges are seen in studies of adults with normal vision (Bailey et al., 1991, Hazel and Elliott, 2002, Rosser et al., 2003), and Beck et al. (2003) found slightly greater variability in participants with poorer vision compared to the group with better vision. Reeves et al. (1987) made the suggestion that studies where participants have good vision may show less variability because variability is constrained if vision is within 2 lines from the end of the chart, although that does not account for the low values of TRV in cataract patients obtained by Elliott and Sheridan (1988).

Of interest in this thesis is whether variability is less in visual acuity tests with a more crowded format. Table 5.2 summarizes studies which report 95% ranges of TRV for logMAR visual acuity tests with a format other than that of the ETDRS chart. Comparison between these studies is difficult for the same reasons as are outlined above for Table 5.1. The 2 formats with most crowding in Table 5.2 are the logMAR Crowded Test (McGraw et al., 2000) and the COMPlog system (Laidlaw et al., 2008), which both have a line of letters with 0.5 letter-widths separation and a surround box at the same separation. These both have comparatively low values of TRV, but a similar TRV is reported for the Lea Symbols chart (Chen et al., 2006) which has wider separation. Also, the study which compares TRV in several chart formats (Laidlaw et al., 2008) found the same TRV range in amblyopic children with the ETDRS chart and the COMPlog system, with closer spacing. Lovie-Kitchin (1988) found a higher TRV in the Snellen chart (±0.26) than the Bailey-Lovie chart (±0.16). One of the possible explanations here could be the greater consistency of crowding in the Bailey-Lovie chart. So, there is some indication that repeatability of visual acuity measurements is lower in more crowded tests, but the evidence is not conclusive.

Table 5.2 shows previous published ranges for 95% test-retest variation (TRV) for logMAR test formats other than those of the ETDRS or Bailey-Lovie Tests. Unless otherwise stated, best corrected VA was measured.

Study	**Test format**	**Inter-optotype separation (edge-to-edge)**	**Surround box-to-letter separation**	**Participants**	**TRV**
McGraw et al. (2000)	LogMAR Crowded Line of 4 letters in a box	0.5	0.5	Children with normal, uncorrected vision	±0.10
Laidlaw et al. (2008)	COMPlog Line of 5 letters in a box	0.5	0.5	Amblyopic children	±0.12
				Adults with normal vision and pathology	±0.10
	eETDRS single letter in a box		0.5	Adults with normal vision and pathology	±0.16
Beck et al. (2003)	eETDRS single letter in a box		0.5	Children and adults with normal vision and pathology	±0.14
Bourne et al. (2003)	Reduced logMAR (RLM) E chart- 3 'E' optotypes/line	1.0	0.5	Adults with pathology	±0.15
Chen et al. (2006)	Lea symbols in ETDRS-style chart	1.0	none	Normal and amblyopic children	±0.10
Laidlaw et al. (2003)	Compact Reduced logMAR (cRLM) chart with 3 letters/line	0.5	none	Amblyopic children	±0.17
Rosser et al. (2001)	Reduced logMAR (RLM) chart with 3 letters/line	1.0	0.5	Adults with pathology	±0.24

5.1.1 The psychometric function

In measuring visual acuity on a letter chart, there will usually be several lines where the participant is able to read some letters, but not others. This reflects the fact that visual acuity is not a sharp step function. Fluctuations in the optical and neurophysiological systems cause the relation between the percent correct performance in naming a letter and the letter size to vary around the threshold (Carkeet et al., 2001, Tinning and Bentzon, 1986, Wichmann and Hill, 2001). This relationship can be plotted as a sigmoid curve, known as the psychometric function (Figure 5.1). Two statistical parameters are of interest: the threshold acuity and the slope of the function. The threshold acuity is the point on the horizontal axis which corresponds to the value on the vertical axis which lies halfway between 100% correct and the level of random guessing.

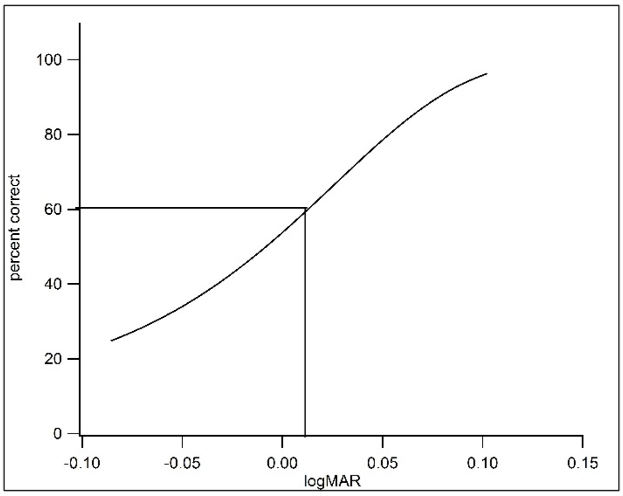


Figure 5.1 Example of a psychometric function, representing performance as percent correct responses plotted against logMAR. The straight line shows threshold estimation for a 5 AFC task, where the guess rate is 20%.

The steepness of the slope of the psychometric function shows how the percentage of correct responses increases with increasing letter size. In a visual acuity test, if correct and incorrect responses are spread over a large number of acuity levels, the derived psychometric function will have a shallow slope and less confidence can be placed in the accuracy of the threshold (Horner et al., 1985). Take 2 hypothetical visual acuity tests, test A and test B. Because of their different design features, the psychometric function derived from test A has a steep slope, whereas that from test B has a shallow slope. In reading chart A, a given variation in performance by the patient will cause a small change in the measured logMAR, whereas the same variation in performance in chart B will cause a greater change in logMAR. On average, then, the SE of estimate for acuity thresholds should be smaller for the chart that produces the steeper psychometric function and the repeatability of the measurements using that chart (which can be predicted from the SE) should be better (McKee et al., 1985). Figure 5.2 helps visualize how a given change in response corresponds to a smaller difference in logMAR where the slope is steeper (in the right panel) than shallower (in the left panel).

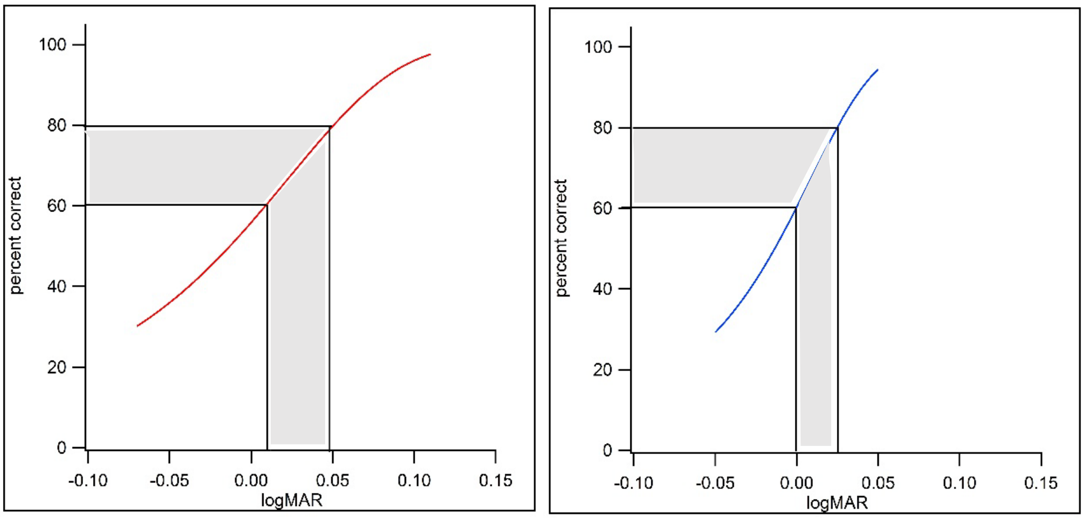


Figure 5.2 shows examples of 2 psychometric functions with different slopes; the function in the right panel has a steeper slope than that in the left panel. The shaded area shows how, when the slope is steeper, a given change in response corresponds to a smaller difference in logMAR.

Slopes of psychometric functions have been found to be fairly constant over wide ranges of acuity levels, but tend to be shallower when uncorrected astigmatism, or amblyopia are present (Horner et al., 1985, Prince and Fry, 1956, Davidson and Eskridge, 1977). Psychometric functions for individual Sloan letters have been published by Raasch et al. (1998) Alexander et al. (1997) and Plainis et al. (2007). (Alexander et al., 1997) derived psychometric functions for Sloan letters of different sizes by varying the contrast. They found that slopes are steeper for large letters than small ones. Further, the slopes of individual letters cross each other, showing that relative difficulty of letters within the set changes with letter size (Alexander et al., 1997, Raasch et al., 1998). Improved repeatability has been found where a smaller increment between lines is used, e.g. 0.05 logMAR rather than 0.1 logMAR i.e. using a finer scale of measurement (Arditi and Cagenello, 1993), or by doubling the number of letters used per line (Raasch et al., 1998). Carkeet et al. (2001) used frequency-of-seeing data to calculate probit size under different conditions of optical blur and found greater reliability under conditions of optical focus than defocus. The authors also recommended letter-by-letter scoring, particularly in cases of optical defocus where the psychometric function slope is shallower.

It has been shown that crowding affects the measured threshold (Chapters 2 and 4). So here I am interested in whether crowding also influences the slope of the psychometric function. The research question is:

> What is the effect of crowding on the psychometric functions derived from visual acuity measurements in adults and children?

In reading down a letter chart, performance declines as threshold is approached. Where the derived psychometric function of a chart has a steep slope, performance on reading down the chart will decline more rapidly than in a chart where the derived psychometric function has a shallow slope. The rate of decline of performance should differ between crowded and uncrowded conditions. It may be that in the crowded conditions, the difficulty caused by the crowding features in addition to decreasing optotype size would cause a more rapid decline in performance than if resolution were the only variable. This leads to the hypothesis that more crowding causes a steeper slope. An alternative hypothesis may be that the crowding features serve to increase the variability of response at more supra-threshold acuity levels than in the uncrowded conditions. This would have the effect of a slower decline in performance and a shallower slope. While it is acknowledged that there are differences in steepness of slope in psychometric functions derived from different individuals (Bach, 2006), the purpose here was to look for mean differences in average slope across several crowding conditions.

5.2 Methods

5.2.1 Tests and participants

I analysed data from some of the tests in Chapter 4: S_0 (isolated letters), $SB_{0.5}$ (single letters with flanking bars at 0.5 optotype separation) and $LC_{0.5}$ (line of letters with letter flankers at 0.5 optotype separation), see Table 5.3 and Chapter 4, section 4.2.2 for more detail. The two crowded tests were chosen as the tests with the simplest and most complex crowding features, representing the extremes of the crowded conditions. Only data from the adults (27 participants) and the younger children (32 participants) were included in the analysis as results from the older children tended to fall between the older and younger groups and would therefore not add to the outcomes.

Table 5.3 Tests used in this analysis. For more detail, see section 4.2.2

Test	Description of crowding	Example presentation
S_0	uncrowded	H
$SB_{0.5}$	bar flankers	
$LC_{0.5}$	letter flankers and linear presentation	F Q U Y A R O H D N S K B W J M T

5.2.2 Procedure

The procedure has been described previously (Chapter 4, section 4.2.3). Briefly, the visual acuity tests were presented on an iPad in a random order and participants were asked to report the letters seen. Viewing was monocular with unlimited viewing time. The acuity range of the tests was logMAR 0.4 to logMAR -0.4 in steps of 0.05 logMAR and for each level of acuity, 5 letters were scored on each test. In the single letter presentations, S_0 and $SB_{0.5,}$ 5 different letters of the same size were shown consecutively. Testing began using a letter size 0.1 logMAR larger than the acuity found from initial screening. Smaller letter sizes were presented in steps of 0.05 logMAR until the termination point was reached, i.e. when 3 or more letters of one size were named incorrectly. If any letters at the starting level were named incorrectly, the next largest size was presented until a size was found where all 5 responses were correct. When a participant was not sure of a letter, they were encouraged once to guess. For the line test with letter flankers, $LC_{0.5}$, participants were asked to read all the letters on the middle row but only the central 5 letters were scored. Pointing at the letters by the examiner was not used under any test condition.

5.2.3 Data analysis

For each participant, the number of correct responses (0-5) was recorded for each acuity level, from the supra-threshold level at which testing began, to the termination point, where 3 or more letters were named incorrectly. Data were pooled across participants to build up psychometric functions for each test. Stimulus size data were normalized to each participant's threshold on that chart (Raasch et al., 1998). In this way, letter size was adjusted according to each participant's threshold for that test. Threshold values were taken from the letter-by-letter scoring method, not from the psychometric functions subsequently plotted. A 'scaled size' value was calculated by subtracting each participant's threshold logMAR acuity from the logMAR presented. Thus the scaled size at the participant's acuity level was zero and each subsequent larger line was 0.05 larger than the previous size. The scaled size of the line lower than the participant's acuity was -0.05, the next -0.1 etc. Table 5.4 shows an example of data from 3 participants. Thus, rather than plotting individual slopes for each participant, data were pooled across participants and the psychometric functions were determined from the pooled data set.

Table 5.4 (overleaf) shows data from 3 participants from one of the tests. The top panel shows the number of letters named correctly for each acuity level shown. The scaled size is calculated by subtracting the participant's threshold logMAR from the logMAR presented. The bottom left panel shows collation of data across participants. Only one level was included with all 5 letters seen. The bottom right panel shows percent correct and scaled size for the 3 participants (i.e. the first and third columns from the bottom left panel), sorted by value of percent correct. These data were then combined with those from the remaining participants in the group, plotted and fit with a Weibull function.

presented logMar	**participant 1** number correct	scaled size	**participant 2** number correct	scaled size	**participant 3** number correct	scaled size
0.30	5	0.30	5	0.52	5	0.28
0.25	5	0.25	5	0.47	5	0.23
0.20	5	0.20	5	0.42	5	0.18
0.15	5	0.15	5	0.37	3	0.13
0.10	5	0.10	5	0.32	3	0.08
0.05	5	0.05	5	0.27	4	0.03
0.00	3	0.00	5	0.22	4	-0.02
-0.05	2	-0.05	5	0.17	3	-0.07
-0.10			4	0.12	1	-0.12
-0.15			4	0.07		
-0.20			3	0.02		
-0.25			4	-0.03		
-0.30			2	-0.08		
-0.35						
-0.40						
threshold logMAR	0.00		-0.22		0.02	

participant	**percent correct**	**number correct**	**scaled size**
1	100	5	0.05
	60	3	0.00
	40	2	-0.05
2	100	5	0.17
	80	4	0.12
	80	4	0.07
	60	3	0.02
	80	4	-0.03
	40	2	-0.08
3	100	5	0.18
	60	3	0.13
	60	3	0.08
	80	4	0.03
	80	4	-0.02
	60	3	-0.07
	20	1	-0.12

percent correct	**scaled size**
100	0.05
100	0.17
100	0.18
80	0.12
80	0.07
80	-0.03
80	0.03
80	-0.02
60	0.00
60	0.02
60	0.13
60	0.08
60	-0.07
40	-0.05
40	-0.08
20	-0.12

Results were combined for all participants within a group, although for each participant, only 1 level was included with all 5 letters seen so as not to include a large amount of supra-threshold data. The number of letters correct was converted to a percent correct and plotted against scaled size. Scaled logMAR was averaged for each of the 5 percent correct points (20%, 40%, 60%, 80% and 100%) and the data were entered into Igor Pro Software (Wavemetrics, Lake Oswego, Oregon, USA) and fitted with a Weibull function (Pelli et al., 1988) defined as:

$$p=1-(1-g)\ \exp[-10^{b(x-t)}]$$

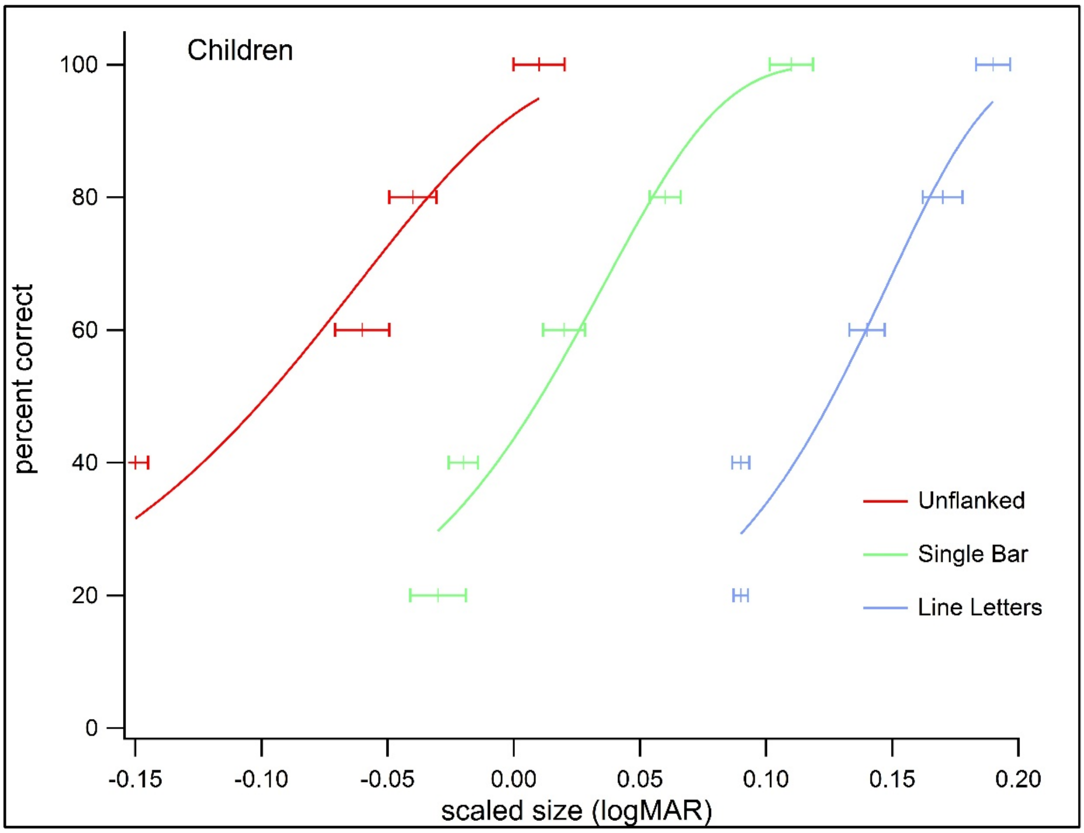
where p is the percent correct for a given letter size, x, in logMAR units, g is the percentage of correct responses equal to 1/n, where n is the number of letters used, i.e.10 and b and t represent the slope and threshold (approx. 60%) respectively. Data from each of the 2 age groups and 3 charts were processed in this way.

5.3 Results

Figure 5.3 shows the averaged data and respective Weibull fits. For ease of viewing, the fitted lines are shown separated horizontally by the difference in mean logMAR between the relevant charts for the age groups (Table 5.5).

Table 5.5 shows mean logMAR (and SE) for the 2 age groups and 3 tests in this analysis.

age	S_0 H	$SB_{0.5}$ C	$LC_{0.5}$ FQUYA ROHDNSK BWJMT
4-6	-0.09 (0.02)	0.03 (0.01)	0.14 (0.04)
adults	-0.18 (0.02)	-0.10 (0.01)	-0.11 (0.01)


Children
percent correct
scaled size (logMAR)
100
80
60
40
20
0
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20
Unflanked
Single Bar
Line Letters

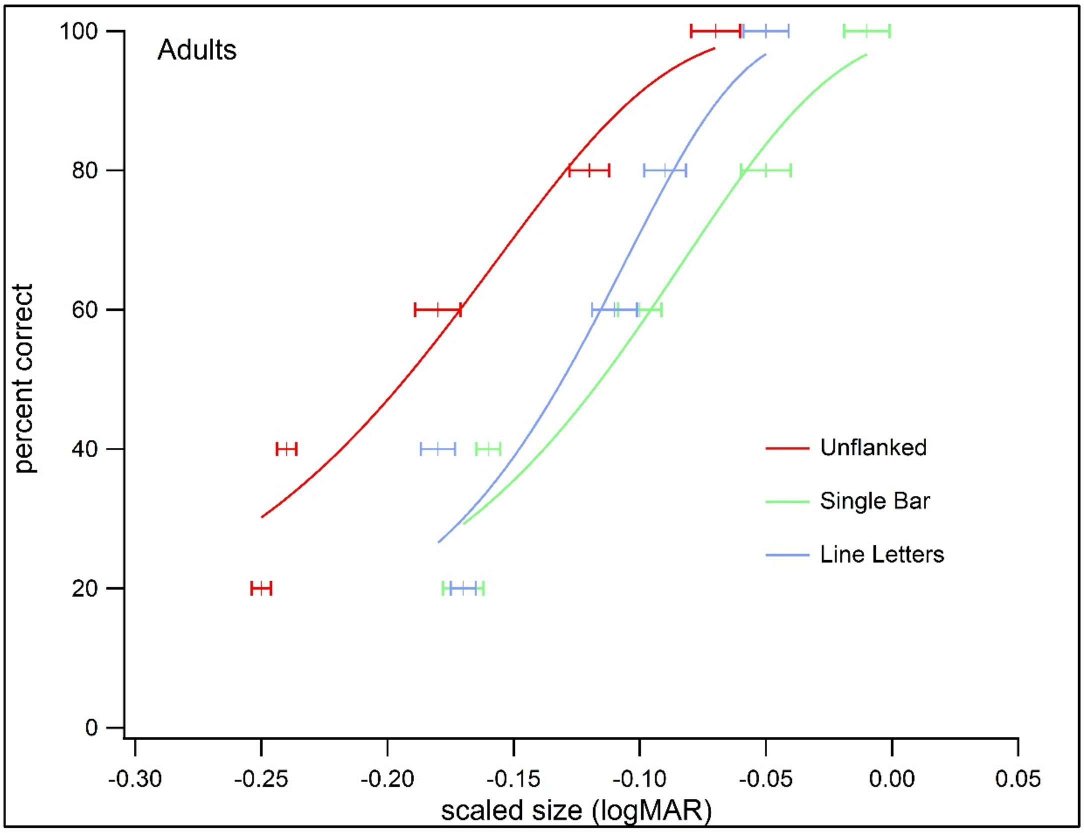

Adults
percent correct
scaled size (logMAR)
100
80
60
40
20
0
-0.30
-0.25
-0.20
-0.15
-0.10
-0.05
0.00
0.05
Unflanked
Single Bar
Line Letters

Figure 5.3 (previous page) shows percent correct plotted against mean scaled logMAR for the 3 letter tests in the children (top panel) and adults (bottom panel). The curves represent the fitted Weibull functions: red shows the unflanked condition; green, the single letter with bar surrounds; blue, the line of letters with letter surround. For clarity, the curves have been shifted horizontally by the difference in mean logMAR between the relevant charts for the age groups. Error bars represent ±1SE.

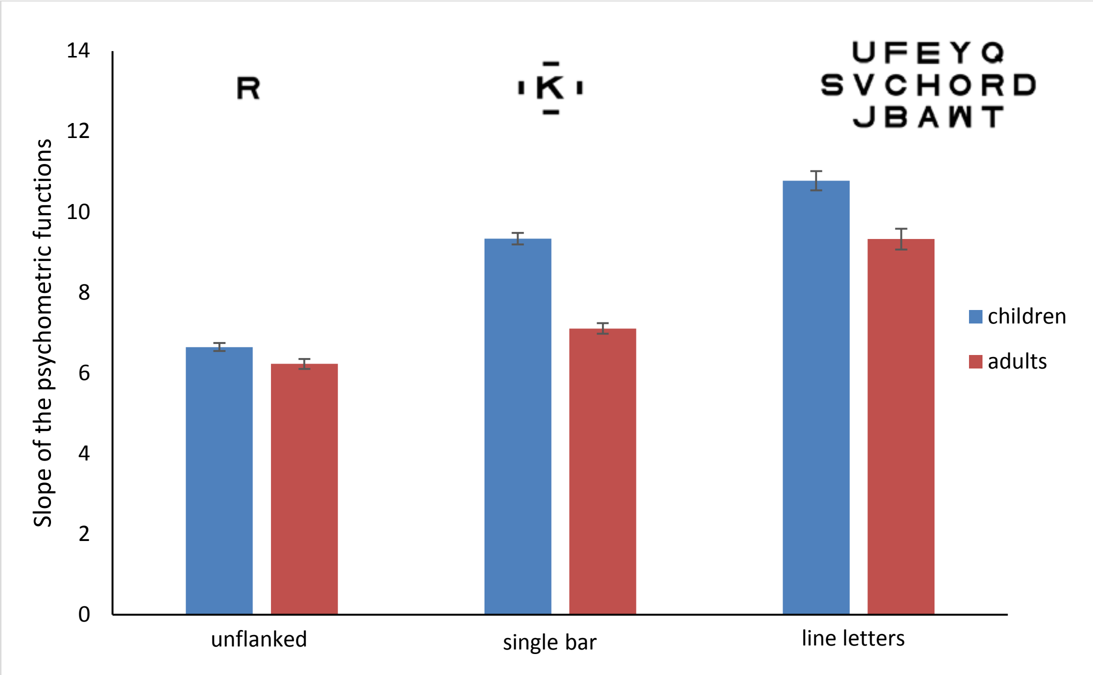


Figure 5.4 compares the slopes of the psychometric functions for the 3 tests in adults and children. Error bars represent ±1SE.

Table 5.6 shows the slopes of the psychometric functions ±1 SD

	S_0 H	$SB_{0.5}$ C	$LC_{0.5}$ FQUYA ROHDNSK BWJMT
children	6.6±1.3	9.3±1.9	10.8±2.4
adults	6.2±1.4	7.1±1.4	9.3±2.6

In both age groups, the slopes of the functions increase with increasing crowding features (Table 5.4 and Figures 5.2 and 5.3). Student's t-tests were performed comparing the slopes of the psychometric functions across the 3 crowding conditions and 2 age groups (Soper, 2014), using the Bonferroni correction. There were significant differences between all the 3 slopes for the children and the adult groups (p<0.001) (Tables 5.5 and 5.6). In comparing adults to children, the differences in slopes were significant in the 2 crowded conditions (p<0.001), but not in the unflanked condition.

Table 5.7 shows results of t-tests of inter-test comparisons of the slopes of the psychometric functions for the 3 tests in children and adults. Using the Bonferroni correction, significance becomes 0.05/n =0.006

Tests	children	adults
Uncrowded vs single bar	t=15.64 p<0.001	t=4.97 p<0.001
Single bar vs line letters	t=5.18 p<0.001	t=7.64 p<0.001
Line letters vs uncrowded	t=15.88 p<0.001	t=10.83 p<0.001

Table 5.8 shows results of t-tests comparing the slopes of the psychometric functions for adults and children for the 3 tests. Using the Bonferroni correction, significance becomes 0.05/n =0.006

Children vs adults	
Uncrowded	t=2.69 *p*=0.008 NS
Single bar	t=11.67 *p*<0.001
Line letters	t=4.10 *p*<0.001

5.4 Discussion

Psychometric functions describing percentage of correct responses as a function of letter size were determined in 2 groups of participants, young children and adults, using 3 different visual acuity tests with various levels of crowding. Slopes were comparable to published data. Alexander et al. (1997) plotted Weibull functions of percent correct vs logMAR for the Sloan letter set. Mean values for the slopes of single Sloan letters were in the range of 6.8-10 for 3 participants.

5.4.1 Comparison of tests

In both the young children and adult groups, psychometric functions became steeper as more crowding features were introduced to the tests. In the crowded tests, the slopes were steeper in the sample of children than the adults, probably reflecting greater crowding in children of this age than in adults (Atkinson et al., 1988, Atkinson and Braddick, 1982). In the adults, the 2 crowded tests had similar thresholds (mean logMAR), yet the linear test had a steeper slope. On the basis that a steeper slope may infer better repeatability, these findings would suggest that due to the crowding, the linear test should have better repeatability (smaller TRV).

Raasch et al. (1998) studied repeatability of visual acuity measurements with 3 different letter separation conditions, 0.8x, 1.0x and 1.25x letter width and found no difference in test-retest discrepancy. This would not be expected under our hypothesis that more crowding leads to better repeatability, but it is likely that any increase in crowding due to changes in letter separation were too small for the adult subjects in Raasch's study, where the smallest spacing was greater than our separation (0.5x letter width).

Despite the plethora of studies showing repeatability of visual acuity tests, no published studies were found which compared the slopes of psychometric functions between visual acuity tests, although some support for our finding was found in a conference abstract (Reich and Hoyt, 2002). In several studies (Greenwood et al., 2009, Parkes et al., 2001), psychometric functions were plotted, the slopes of which became shallower in crowded conditions compared to uncrowded. In these studies, size of the target was not varied and the effect of flankers was to cause increased uncertainty. In our study, a reduction in size of the targets caused a reduction in performance towards the limit of resolution, which was confounded with closer flanking elements, so a different result might be expected from a study in which size was not a variable. We found that crowded targets caused an increased level of difficulty in addition to resolution as the letters became smaller, thus causing performance to deteriorate more quickly than with uncrowded targets.

5.4.2 Comparison of age groups

The slopes of the psychometric functions were steeper for the children than the adults and these findings were statistically significant for the 2 crowded tests. These results appear to be inconsistent with those of Jeon et al. (2010), who used a boot-strapping technique to create frequency of seeing curves for single letter acuity in children and adults. They found a shallower slope in the measurements from the youngest children (aged 5) than in those from the older children and adults. In the current study, there was no significant difference in the slopes between young children and adults in the unflanked condition. As commented previously (section 2.5.4), the mean visual acuity was worse for the 5 year olds in the study by Jeon et al than in our youngest group, possibly reflecting a more difficult visual task in their study and consequently, more variable responses.

The current findings of steeper slopes in children than adults in the crowded tests but not the uncrowded test provides indirect evidence that crowding is the factor which is causing the slopes to be steeper in young children. We know that there is a greater depth of crowding in young children than adults in the configurations tested here (Chapter 4).

5.4.3 Conclusions

This study provides new evidence regarding the effect of crowding on the slopes of the psychometric functions underlying visual acuity measurements. Average group data shows that slopes become significantly steeper with increasing crowding features for both young children and adults with normal vision. Slopes for individual subjects were not measured. The slopes were steeper for the group of young children than the adults, probably reflecting the greater crowding in the young children. Based on the argument that a steeper slope will reduce the variability of repeated measurements, it may be possible to infer from these results that the test-retest repeatability of visual acuity measurements could be enhanced through the use of more crowded visual acuity tests in clinical practice. However, a conclusion cannot be drawn without a further study to measure repeatability directly between crowded and uncrowded tests in children and adults.

Chapter 6

Foveal crowding in strabismic and mixed strabismic-anisometropic amblyopes

6.1 Purpose

As described in Chapter 1, crowding which does not scale with acuity is found in some amblyopic eyes (Stuart and Burian, 1962, Flom et al., 1963b, Levi and Klein, 1985). This elevated crowding could be as a result of abnormal contour interaction, deficits in gaze control or attention or a combination of these (Asper et al., 2000). In anisometropic amblyopia, contour interaction is thought to scale with unflanked acuity, whereas in strabismic amblyopia, disproportionate contour interaction may be expected (Hess et al., 2001, Levi et al., 2002a, Bonneh et al., 2004, Hariharan et al., 2005). Abnormal gaze control may reduce acuity in line charts, or reading long strings of letters, where accurate fixation is required (Regan et al., 1992, Giaschi et al., 1993, Bedell et al., 2015). Attention deficits have been found in amblyopic observers in studies involving tracking paradigms (Ho et al., 2006, Secen et al., 2011, Huurneman and Boonstra, 2015) and enumeration of objects in an array (Sharma et al., 2000) or presented in rapid succession (Popple and Levi, 2008). In normally sighted adults, attention is not thought to contribute to foveal crowding (Atkinson, 1991, Norgett and Siderov, 2014, Leat et al., 1999), but in amblyopic adults, it is possible that these higher level attention deficits could influence the ability to select the target from distractor in a static visual acuity test.

Here, visual acuity was measured in both eyes of amblyopic adults using some of the custom designed tests from Chapter 4 to look for the relative contributions of contour interaction, gaze control and attention to the overall crowding effect.

Amblyopic children were not recruited to avoid the confound between developmental changes in crowding and abnormal crowding due to amblyopia.

The research questions are:

1. What are the relative contributions of contour interaction, gaze control and attention on crowded acuity in adults with strabismic or mixed strabismic/anisometropic amblyopia?
2. Can mis-naming errors explain any differences between results of crowded visual acuity tests in the amblyopic and fellow eyes of participants with strabismic or mixed strabismic/anisometropic amblyopia?

6.2 Methods

6.2.2 Participants

Adult participants with amblyopia were recruited from the local community. Amblyopia was defined as at least 2 lines difference in visual acuity between the 2 eyes in the absence of structural abnormality of the eye or visual pathway. Anisometropia was defined as greater than 1D difference between the eyes in the most anisometropic meridian with no manifest ocular deviation or history of surgery. All participants underwent a detailed assessment prior to testing with the experimental tests, including fundus check, refraction, logMAR acuity (Thompson logMAR chart, Thomson Software Solutions, Hatfield, Hertfordshire, UK), stereopsis using the Lang II Stereotest (Lang-Stereotest, Küsnacht, Switzerland) and cover test for distance and near fixation. Any heterophoria or heterotropia found was measured by prism cover test. History of previous treatment was also recorded. Clinical details of the participants are given in Table 6.1. Written, informed consent was obtained from all participants after all the procedures were explained to them.

Ethical approval for the study was obtained from the University Research Ethics Panel and the study followed the tenets of the Declaration of Helsinki.

Five participants with strabismic amblyopia and 6 participants with mixed strabismic/anisometropic amblyopia were recruited, but it proved difficult to recruit participants with pure anisometropic amblyopia; only 2 were recruited. The number of participants with strabismic amblyopia or mixed strabismic/anisometropic amblyopia was sufficient to obtain a power of 80% at the 5% level (one tailed) for an effect size of 0.15 logMAR.

Table 6.1 shows participant clinical details. Esot: esotropia; exot: exotropia; hypot: hypotropia; hypert: hypertropia; micro: presumed mictrotropia - no movement detected on cover test; ^: prism dioptres

Initial	Age/ gender	Eye/type	Surgery/ patching	Alignment	Stere-opsis	Refractive error	logMAR
KW	56/F	R strab	No/Yes	Micro	600”	R +2.50 L +2.50/-0.50 x 90	0.62 -0.14
FD	39/F	R strab	Yes/Yes	Micro	200”	R -1.00/-1.00 x 180 L -0.50/-0.75 x 140	0.44 -0.08
MP	40/M	L strab	No/ Yes	8^ esot	none	R +0.50/-0.50 x 170 L plano	-0.20 0.80
BS	75/F	R strab	No/Yes	12^ esot	none	R +2.50/-0.25 x 110 L +2.25/-0.25 x 70	0.36 0.10
JP	62/M	L strab	No /Yes	3^ esot 2^ hypot	none	R +2.00/-1.25 x 170 L +1.75	0.00 0.56
JB	61/F	R strab/ mixed	Yes/Yes	5^ esot	none	R +3.75/-0.50 x 80 L +1.00/-1.25 x 95	0.60 0.00
PD	49/F	L strab/ mixed	No/No	4^ esot	none	R -2.50/-1.00 x 160 L +0.75/ -0.50 x 10	-0.08 0.44
PG	69/M	L strab/ mixed	Yes/Yes	6^ esot	none	R plano/-1.25 x 80 L +2.50/-1.25 x 10	0.02 0.66
LM	23/F	R strab/ mixed	Yes/Yes	40^ accom esot Micro with Rx	none	R +7.00/-2.00 x 40 L +6.50/-0.50 x 140	0.10 -0.10
TW	43/M	R strab/ mixed	Yes/Yes	4^ R hypot and 10^ esot	none	R +1.50 L plano	0.92 0.02
MOL	37/F	L strab/ mixed	No/Yes	24^ accom esot. Micro with Rx	none	R +5.00/-3.50 x157 L +6.50/-5.00 x 20	0.20 0.78
MR	62/M	aniso	No/No	3^ esop	200”	R +4.50/-1.50 x 85 L +5.50/-1.25 x 110	-0.1 0.34
HK	21/F	aniso	No/Yes	ortho	1200”	R +0.50 L +1.25/-0.25 x 105	-0.04 0.28

6.2.2 Tests

The letter tests, $SB_{0.5}$, $SC_{0.5}$, $LB_{0.5}$ and $LC_{0.5}$ from Chapter 4 were used with an additional 3 tests (Table 6.2). It was recognized in Chapter 4 that although there were 5 scored letters in each of the 2 linear tests, the task in $LC_{0.5}$ was to read 7 letters and only 5 in $LB_{0.5.}$ An additional test, LB7 was created in the same way as $LB_{0.5}$, with 7 Sloan letters rather than 5, although only the central 5 are scored. This enabled comparison between flanker types in linear tests with 7 letters. In addition, 2 tests were created in the same way as $SC_{0.5}$ and $LC_{0.5}$, but with the use of Sloan letter flankers rather than non-Sloan letters- SCsl and LCsl. This was to allow further error analyses because when non-Sloan flankers were used, the 10 AFC procedure did not allow for non-Sloan letter responses. As all the tests in this chapter have the same edge-to-edge separation of letters and flankers of 0.5 letter widths, the subscript 0.5 will no longer be used.

Table 6.2. shows the tests used in the study, with an example presentation of each. Letters were presented in single (S) or linear (L) format with bar (B) or character (C) flankers. The edge-to-edge separation was 0.5 letter widths in each of the crowded tests.

Test	Sloan letter target	Flanker type	Example display
S_0	single	no flanks	H
SB	single	bars	C
LB	linear 5 letters	bars	C H D N O
LB7	linear 7 letters	bars	D K C N O R V
SC	single	non-Sloan characters	M A K B J
SCsl	single	Sloan characters	K D H O Z
LC	linear	non- Sloan characters	F Q U Y A R O H D N S K B W J M T
LCsl	linear	Sloan characters	O V K D H R K C Z S V O S R H O N

Letters were constructed in a 5x5 format, with the height and the width of each letter 5 times the stroke width and each test was produced using Adobe Illustrator CS5 (Adobe Systems Incorporated) as previously described (Chapter 4, section 4.2.2). Tests were displayed on an Apple iMac 21.5 inch screen (Apple Inc. Cupertino, California) with a resolution of 1920x1080 at 102.46 pixels per inch, so 1 pixel subtended 0.2' of arc at a test distance of 4m. Background luminance of the display was 266 cd/m^2, resulting in a letter Weber contrast of -92%. The acuity range of the tests was logMAR 0.6 to logMAR -0.4 in steps of 0.05 logMAR and for each acuity level, 5 letters were scored in each test. In the single letter presentations, 5 different letters of the same size were shown consecutively. Edge-to-edge spacing between letters and flankers was 0.5 letter widths for all tests.

6.2.3 Procedure

Testing was carried out in a room with lighting adequate for visual acuity testing (National Academy of Sciences-National Research Council Committee on Vision,1980), approximately 100 lux. Following refraction and screening tests, the experimental tests were viewed by each eye of eligible participants wearing best corrective lenses. For each participant, the non-amblyopic eye was tested first. Participants sat 4m from the screen and held a card showing the ten Sloan letters. A 4m testing distance was chosen to maximize the size of the largest letter size within the confines of the screen size and test room. The 8 experimental tests were shown in a random order, different for different individuals and participants were allowed unlimited viewing time. Testing began using a letter size 0.1 logMAR larger than the acuity measured following refraction. Smaller letter sizes were presented in steps of 0.05 logMAR until the termination point was reached, at which 3 or more letters of one size were named incorrectly. If any letters at the starting level were named incorrectly, the next largest size was presented until a size was found where all 5 responses were correct. Where the logMAR 0.6 letters were not all read correctly at 4m, viewing distance was decreased to 2m, with the participant's refractive correction and the logMAR score adjusted appropriately. For the single letter tests with letter flankers, (SC and SCsl), participants were asked to read the middle letter only. For the line tests, (LC and LCsl), participants were asked to read all the letters on the middle row but only the central 5 letters were scored. For the 7 letter line with bar flankers, LB7, again, only the central 5 letters were scored. When a participant was not sure of a letter, they were encouraged once to guess, or in tests

SC or LC, if they named a non-Sloan letter, they were directed to retry from the Sloan letter set. Pointing at the letters by the examiner was not used under any test condition.

All responses were recorded on a spreadsheet by the examiner and letter-by-letter scoring was used. For the line tests, if a participant read the incorrect number of letters in a line, without indicating that they were leaving one out, the responses were recorded in the order and position they were read. Baseline data using test S_0 (unflanked logMAR), were used to normalise subsequent results to minimise any potential confound between letter size and inter-letter spacing for different acuity sizes (Levi, 2008).

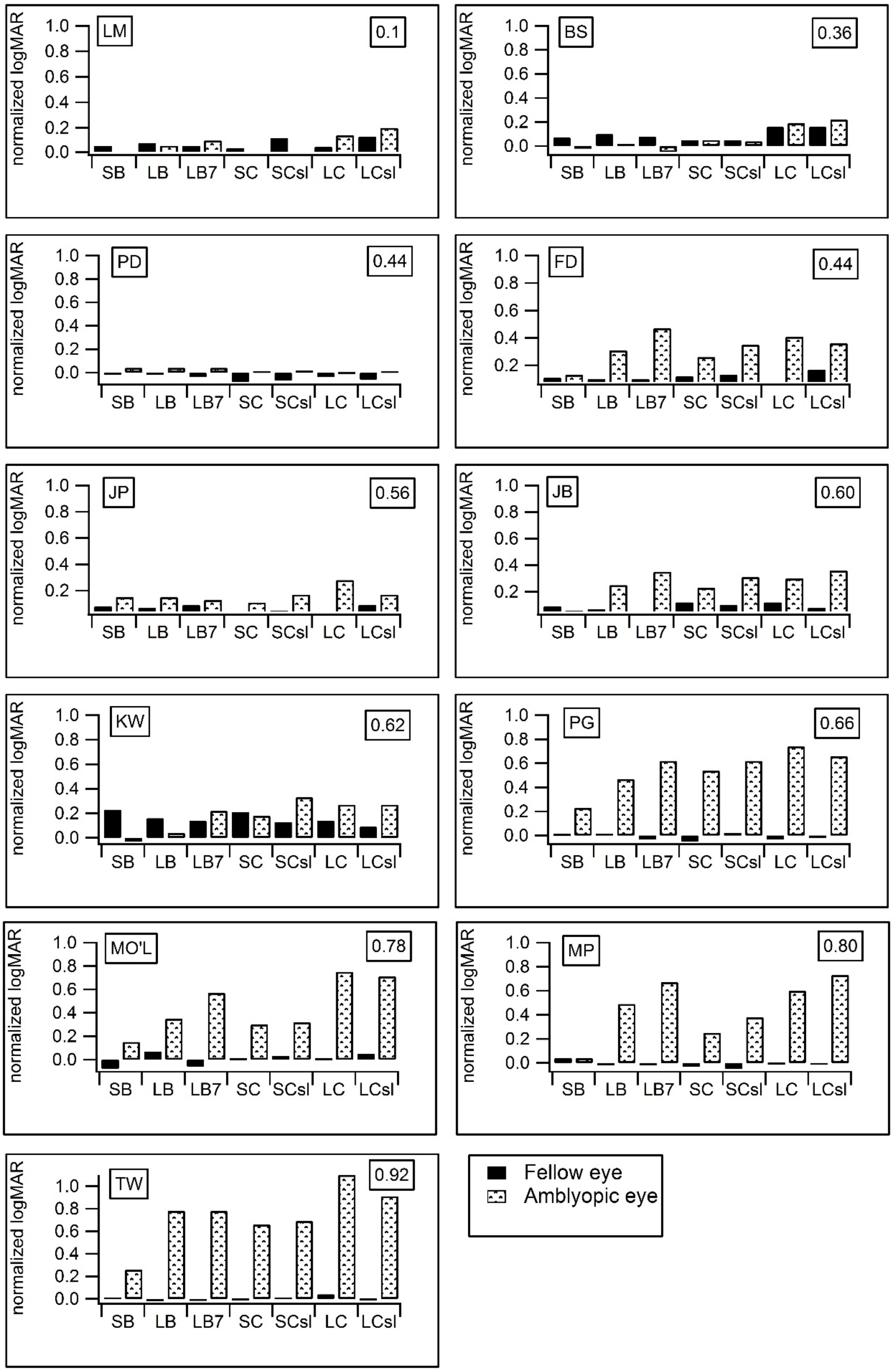
6.2.4 Data analysis

Data were analysed using paired t-tests and repeated measures ANOVA with a Greenhouse-Geisser correction for violation of sphericity applied (Keppel, 1982). Thus, an increase in Type I errors is avoided where the differences across tests are not the same for each of the age groups. Post-hoc analyses with Tukey HSD correction were performed as required (Statistica StatSoft, Ltd, Tulsa). Letter naming errors were also analysed in the two line tests, LB and LC and in the single letter test, SCsl, to investigate any difference in pattern between tests and amblyopic or fellow eyes. Errors were defined as either ‘adjacent’ if the response letter was adjacent horizontally to the target letter (either left or right, top or bottom), or ‘random’ if any other letter was named. In the line tests with bar flankers, LB and LB7, errors pertaining to just the central 3 or 5 letters respectively were analysed, as the end letters only had one possible adjacent option. In the line tests with letter flankers, LC and LCsl, errors pertaining to the central 5 letters were analysed. Four analyses were carried out. The first one examined whether the adjacent errors in the line tests LB, LB7 and LC were anything other than random; the second examined the frequency of right and left adjacent errors in the line tests LB and LC; the third examined whether the adjacent errors in the single letter test, SCsl were anything other than random and the fourth looked for a difference in frequency of adjacent and random errors between amblyopic and fellow eyes in SCsl. Chi square tests were performed to assess statistical significance.

6.3 Results

6.3.1 Individual participants

Figure 6.1 shows logMAR in each of the crowded tests for the individual participants with strabismic or mixed strabismic/anisometropic amblyopia, normalized to the unflanked acuity. Visual acuity in the amblyopic eye, as shown from the initial screening is displayed in the top right hand side of each panel in order of increasing depth of amblyopia. In this data set, a general trend towards an increase in crowding with depth of amblyopia is evident.



LM
0.1
BS
0.36
PD
0.44
FD
0.44
JP
0.56
JB
0.60
KW
0.62
PG
0.66
MO'L
0.78
MP
0.80
TW
0.92
normalized logMAR
1.0
0.8
0.6
0.4
0.2
0.0
SB
LB
LB7
SC
SCsl
LC
LCsl
Fellow eye
Amblyopic eye

Figure 6.1 (previous page) shows logMAR for the amblyopic (dotted bars) and fellow (black bars) eyes for each of 11 strabismic and mixed strabismic/anisometropic adults, normalized to the uncrowded logMAR for each of the crowded conditions. LogMAR in the amblyopic eye as derived from initial screening is shown in the top right corner. An example of each display is shown in the key below Figure 6.3.

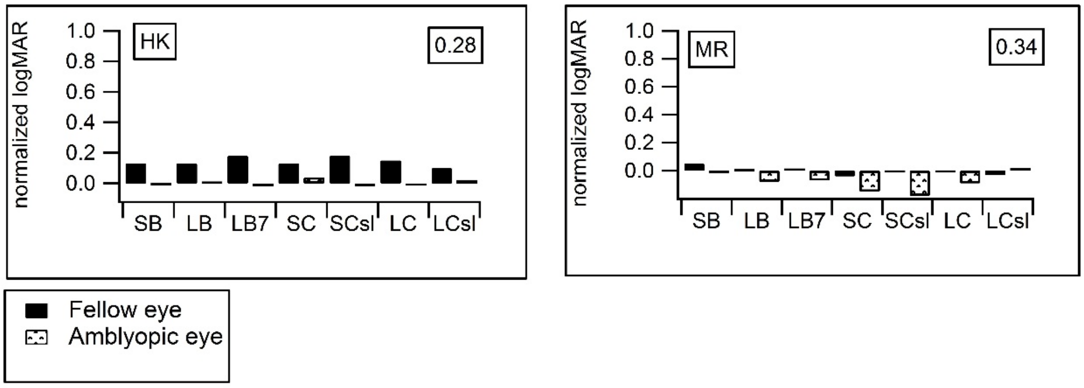


Figure 6.2 shows logMAR for the amblyopic (dotted bars) and fellow (black bars) eyes for each of 2 anisometropic adults, normalized to the uncrowded logMAR for each of the crowded conditions. LogMAR in the amblyopic eye as derived from initial screening is shown in the top right corner. An example of each display is shown in the key below Figure 6.3.

Figure 6.2 shows normalized logMAR in each of the crowded tests for each of the 2 participants with anisometropic amblyopia. Neither of these participants showed crowding in their amblyopic eye in any of the crowded conditions. There is evidence in the literature that with high contrast, letter or letter-like stimuli in foveal viewing, the crowding in the amblyopic eye of anisometropic amblyopic observers scales with acuity (Bonneh et al., 2004, Greenwood et al., 2012, Song et al., 2014). The analysis was therefore conducted only on the strabismic/ mixed strabismic/anisometropic group.

6.3.2 Strabismic and mixed strabismic/anisometropic amblyopes

For the participants in this group, mean logMAR was better than 0.00 (6/6) in their non-amblyopic eye in all the tests. Before normalizing the results, paired t-tests were performed to look for a difference between the uncrowded condition, S_0, and the single letter condition with bar flankers, SB. There was a significant difference between these 2 tests for both amblyopic and fellow eyes, $p<0.05$, showing an effect of contour interaction in each. When logMAR was normalized to the unflanked condition, there was no significant difference between amblyopic and fellow eyes in SB, $p=0.43$, showing no additional contour interaction in the amblyopic eyes than the fellow eyes in this condition.

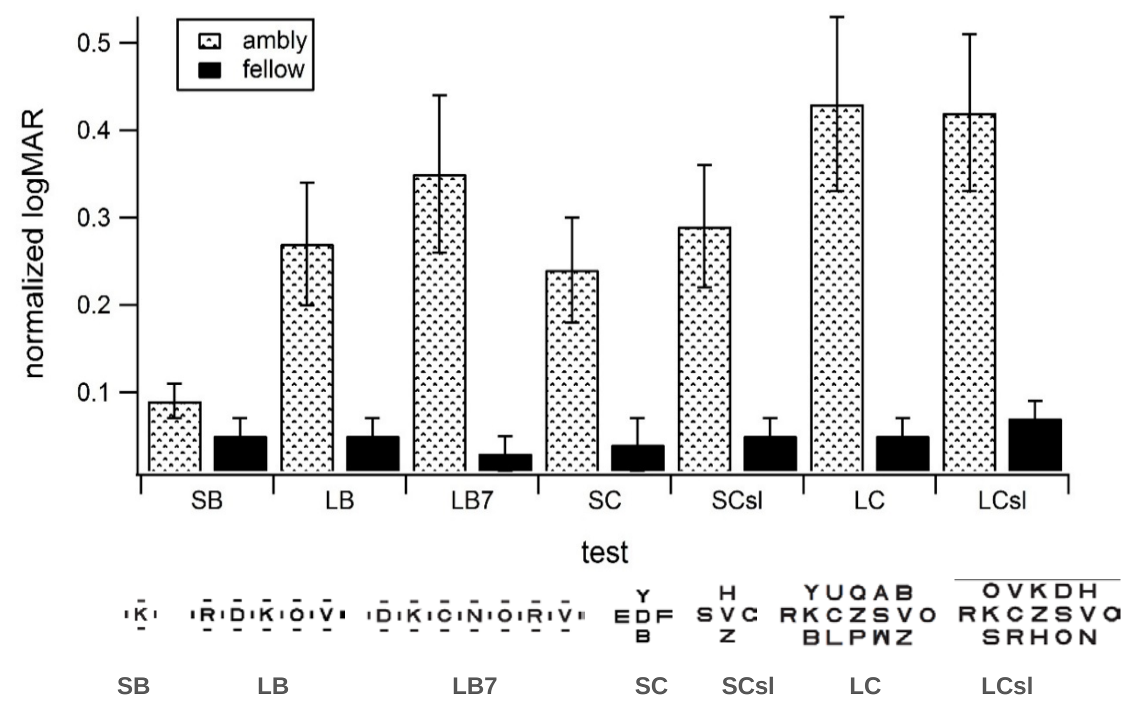


Figure 6.3 shows mean logMAR for the amblyopic (dotted bars) and fellow (black bars) eyes of 11 strabismic and mixed strabismic/anisometropic amblyopic adults, normalized to the uncrowded logMAR for each of the crowded conditions. An example of each display is shown in the key below the chart. Edge-to-edge target-flanker separation is 0.5 letter-widths in each test. Error bars represent ±1SE.

Table 6.3 shows mean, normalized logMAR (and SE) for the 7 crowded conditions for the fellow and amblyopic eyes of the strabismic participants.

	SB	**LB**	**LB7**	**SC**	**SCsl**	**LC**	**LCsl**
Fellow eyes	0.05 (0.02)	0.05 (0.02)	0.03 (0.02)	0.04 (0.03)	0.05 (0.02)	0.05 (0.02)	0.07 (0.02)
Amblyopic eyes	0.09 (0.03)	0.27 (0.07)	0.35 (0.09)	0.24 (0.06)	0.29 (0.07)	0.43 (0.10)	0.42 (0.09)

Figure 6.3 and Table 6.3 show mean, normalized logMAR across the crowding conditions for amblyopic and fellow eyes. A one-way repeated measures ANOVA for

the group of amblyopic eyes yielded a significant main effect of test F(2.18, 21.84) = 13.23, p<0.001. Post-hoc analysis (Tukey test) showed mean, normalized logMAR in the amblyopic eyes in SB to be different to all the other tests p<0.05. Mean, normalized logMAR in the amblyopic eyes in LC was also different to all the other tests, apart from LCsl. There was no difference in mean normalized logMAR in the non-amblyopic eyes across the tests F(2.50, 24.97)=0.52, p=0.67.

6.3.3 Effect of single vs linear presentation

In the amblyopic eyes, there was more crowding in the linear than the single letter conditions. Mean, normalized logMAR was significantly higher in both the linear tests with bar flankers, LB and LB7, than in the single letter test with bar flanker, SB, (p<0.01). The 7 letter test, LB7 showed a trend towards more crowding than the 5 letter version, LB, but the difference between LB7 and LB was not significant p=0.51. Mean, normalized logMAR was also significantly higher in the linear tests with letter flankers, LC and LCsl than in the single letter test with letter flankers, SC, (p<0.05).

6.3.4 Effect of letter vs bar flankers

In the amblyopic eyes, there was more crowding in the tests with letter - rather than bar - flankers. For the single letter tests, mean logMAR was significantly poorer in both the single letter tests with letter flankers, SC and SCsl, than the single letter test with bar flankers, SB (p<0.05). Mean, normalized logMAR was 0.05 worse in SCsl than SC, but the difference was not significant. In the linear tests, there was also more crowding with letter than bar flankers. Mean, normalized logMAR was significantly worse in LC and LCsl than LB (p<0.05).

6.3.5 Error analysis

LCsl was created so that top and bottom errors could be counted in addition to right and left errors. However, there were too few vertical errors to allow a chi square test to be performed, so errors from LCsl were not included in the following analysis.

Figure 6.4 shows the relative percentages of the different error types in the line tests LB, LB7 and LC in the amblyopic and fellow eyes of the strabismic and mixed strabismic/anisometropic amblyopes. Light grey shading shows random errors, dark shading shows adjacent left errors and diagonally striped shading shows adjacent right errors.

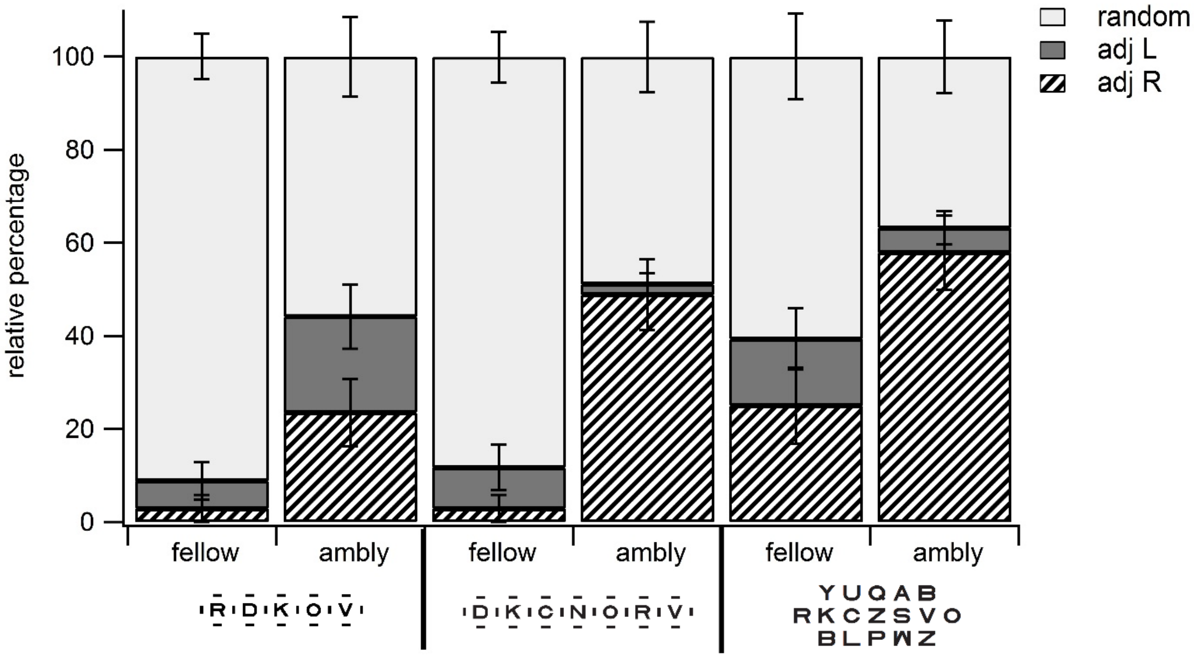


Figure 6.4 shows the relative percentages of the different error types in the line tests, LB, LB7 and LC for the amblyopic and fellow eyes of the strabismic and mixed strabismic/anisometropic amblyopes. Light grey shading shows random errors, dark shading shows adjacent left errors and diagonally striped shading shows adjacent right errors. Error bars represent ±1 SE.

The first analysis examined whether the adjacent errors were anything other than random in the 3 line tests. As there were 2 adjacent letters from 10 possible Sloan letters, the probability of naming an adjacent letter correctly by chance was 0.2. For LB and LB7, for the fellow eye, on average, the adjacent errors were not significantly different to chance (LB: χ^2=2.56, p=0.10; LB7: χ^2=1.44, p=0.23) but for the amblyopic eyes, more adjacent errors occurred than would be expected by chance (LB: χ^2=12.36, p<0.001; LB7: χ^2=26.10, p<0.001). In the line test with letter flankers, LC, on average, more adjacent errors occurred than would be expected by chance for both amblyopic (χ^2=44.24, p<0.001) and fellow eyes (χ^2=6.51, p<0.05).

The second analysis examined the frequency of right and left adjacent errors in the line tests LB and LC. In LB7, Figure 6.4 shows a large proportion of right errors in the amblyopic eyes, although the number of some error types was too low to enable a chi square analysis. In LB the proportion of right and left errors was not different for amblyopic (χ^2=0.07, p=0.80) or fellow eyes (χ^2=0.33, p=0.56). However, in LC, there were more right than left errors for both amblyopic (χ^2=6.24, p<0.05) and fellow eyes (χ^2=5.14, p<0.05).

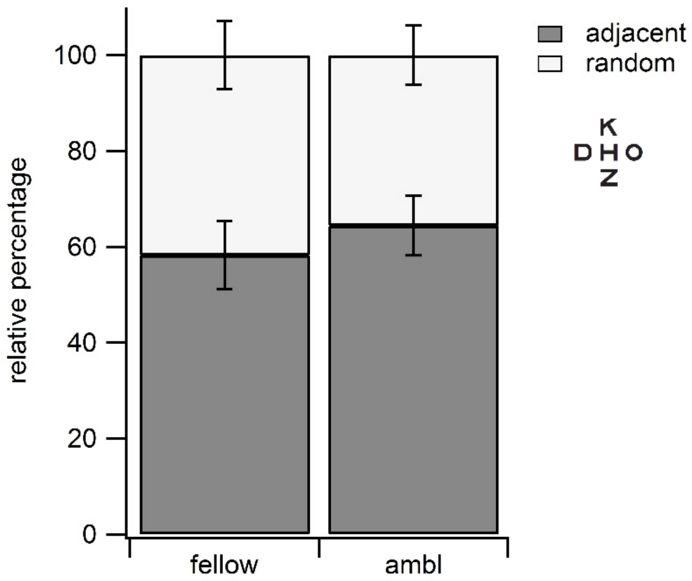


Figure 6.5 shows the relative percentage of error types, adjacent (horizontal and vertical) and random, for amblyopic and fellow eyes of the strabismic amblyopes for test SCsl, an example presentation of which is shown on the right of the chart. Light grey shading shows random errors and dark grey shading shows adjacent errors.

The third analysis examined whether the adjacent errors in the single letter test, SCsl were anything other than random. Figure 6.5 shows the relative proportions of adjacent and random errors in the single letter test, with Sloan letter flankers, SCsl. Here, adjacent errors corresponded to one of the surrounding 4 letters, while any other error was deemed random. The probability of an adjacent error occurring by chance was 0.4. On average, there were more adjacent errors named than would be expected by chance for both amblyopic (χ^2=14.64, p<0.001) and fellow eyes (χ^2=6.72, p<0.05).

The fourth analysis looked for a difference in frequency of adjacent and random errors between amblyopic and fellow eyes in the single letter test, SCsl. There was no difference in proportion of random and adjacent errors in the amblyopic (χ^2=0.19, p=0.67) or fellow eyes (χ^2=0.23, p=0.63).

6.4 Discussion

6.4.1 Summary of findings

A series of custom designed visual acuity tests was used to infer the relative influence of contour interaction, linear versus single presentation and target-flanker similarity on visual acuity (logMAR) in the amblyopic and fellow eyes of a group of amblyopic participants. In common with other reports, there was marked variability of crowding amongst amblyopic participants (Polat et al., 2004, Bonneh et al., 2004, Regan et al., 1992). Due to the difficulty in recruiting purely anisometropic participants, the 2 recruited were not included in the analysis but these showed no elevation of crowding across any of the tests in their amblyopic eyes. As illustrated in Figure 6.6, the pattern of crowding in the group of strabismic and mixed strabismic/anisometropic amblyopic eyes in the experimental tests shows a similar pattern to the results arising from young children. There is an elevation of crowding seen with letter rather than bar flankers and with linear rather than single letter presentations. There is also an additive effect, with highest crowding occurring in the linear presentation with letter flankers. This similarity between performance of strabismic amblyopic eyes and that of the young children lends strength to the view of amblyopia as a poorly matured visual system. Levi and Carkeet (1993) compared a range of visual functions in strabismic amblyopes and young children. They found that some functions, such as peak contrast sensitivity and retinal functions, which develop early, were normal in the strabismic amblyopes, whereas Vernier acuity and grating acuity which develop later were impaired in the strabismic amblyopes. Thus the timeframe in which strabismus exerts its influence on the developing visual system can be inferred. The findings of this study show that in strabismic amblyopia, the visual system is affected before the maturation of crowding is complete.

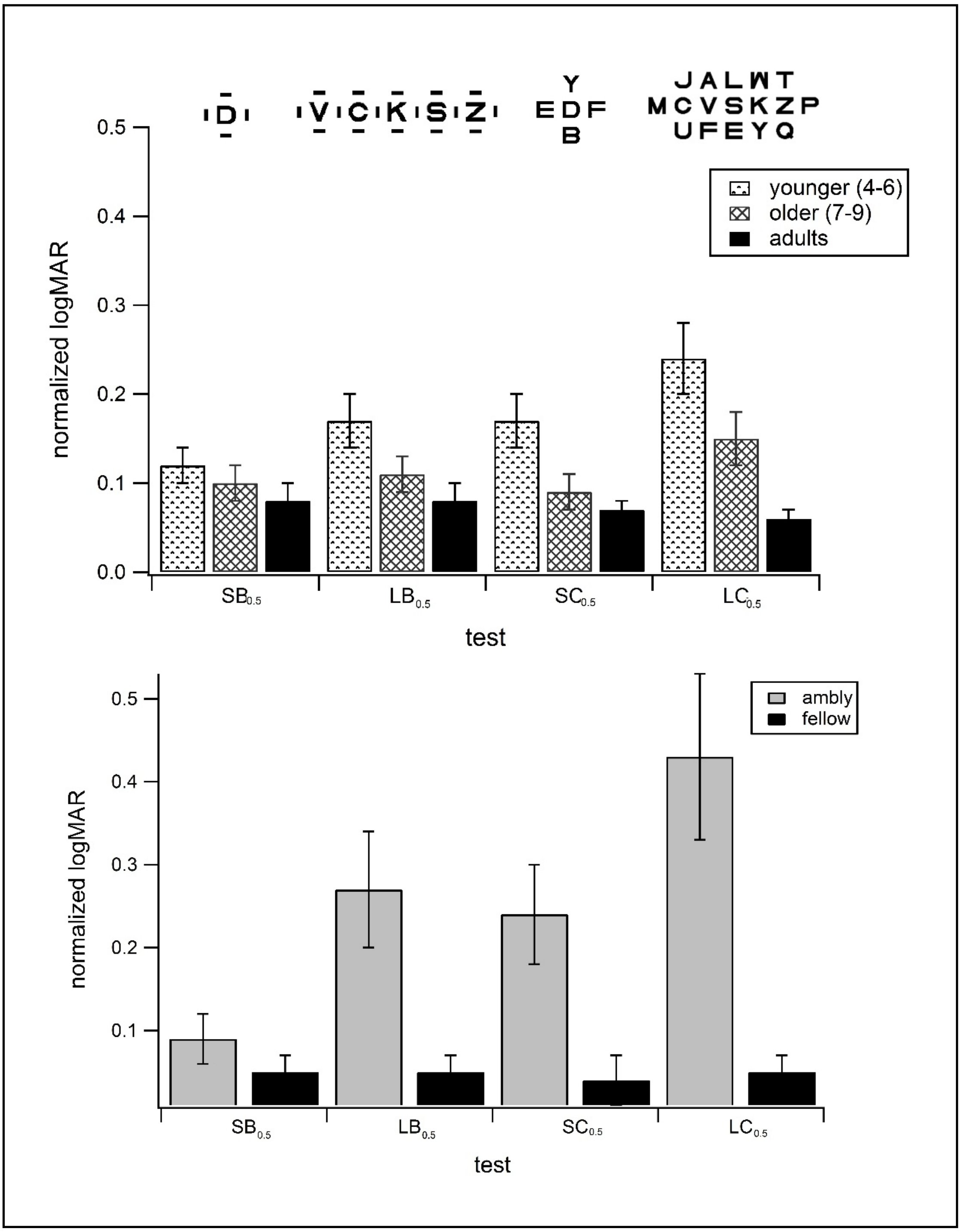


Figure 6.6 compares Figure 4.3 from Chapter 4 (top panel) with the same 4 tests from Figure 6.3: SB, LB, SC and LB (lower panel). The top panel shows mean logMAR, normalized to the unflanked acuity, for the four crowding conditions for younger children, 4-6 yrs (dotted bars), older children, 7-9 yrs, (cross-hatched bars),

and adults (solid bars). The bottom panel shows mean logMAR, normalized to the unflanked acuity, for the four crowding conditions for amblyopic (grey bars) and fellow eyes (black bars) of strabismic and mixed strabismic/anisometropic adults. Error bars represent ±1 SE.

6.4.2 Magnitude of contour interaction

In the group of strabismic and mixed strabismic/anisometropic amblyopes, mean logMAR in test SB was significantly higher than unflanked logMAR in the amblyopic and fellow eyes, showing an effect of contour interaction. The mean normalized logMAR for the strabismic and mixed strabismic/anisometropic group in SB was not significantly different between the amblyopic and fellow eyes. This result shows that for the single letter presentation with bar flankers, on average, contour interaction scaled with acuity in this group. As reported previously (Hess et al., 2001), some individuals showed more contour interaction with their amblyopic eye than their fellow eye whilst for others, elevated crowding was not seen, and the flanked acuity scaled with unflanked acuity (Figure 6.1) (Flom et al., 1963b). This reflected in the inhomogeneity of the group of amblyopes.

6.4.3 Effect of eye movements

In the amblyopic eyes of the strabismic and mixed strabismic/anisometropic group, most of the individual participants showed poorer mean logMAR in the line tests than in the corresponding single letter tests (Figure 6.1) and the same was true for the group means (Figure 6.3). This finding may not be surprising given the extra oculomotor demand in the line tests and both the oculomotor deficits and positional uncertainty experienced in amblyopia (Levi et al., 1987, Hess and Holliday, 1992, Chung et al., 2015, Ciuffreda et al., 1980). Also, see section 1.9.4. Positional uncertainty can lead to a degraded sensory signal, causing increased saccadic drift (González et al., 2012). Kanonidou et al. (2014) showed that strabismic amblyopes made more saccades per line when reading small print with their amblyopic eye. The scoring system used in the current study required letters to be read in order from left to right and responses were scored as incorrect if read in the wrong order. Thus, the positional uncertainty or oculomotor errors may cause the strabismic amblyope to lose their place when reading the line of letters and increase the probability of making an incorrect regression. Performance in the single letter test with bar flankers, SB, should be least affected by positional uncertainty/ oculomotor errors as there is only one letter in the display. Observers viewing the single letter with letter flankers, SC, and the line of letters with letter flankers, LC, may be expected to show increasingly poor performance with increased positional uncertainty/ oculomotor errors, because of the task demands of identifying the target letter to be read and the number of possible letters in the displays. Figure 6.3 shows that this was indeed the case for the amblyopic eyes.

The error analysis showed more adjacent errors in the amblyopic than fellow eyes in all the line tests, (Figure 6.4), inferring the pressure of increased positional uncertainty and/or oculomotor demands, and in the tests where 7 letters were to be read, LB7 and LC, there was a greater proportion of right than left errors than in the 5 letter test, LB, inferring that participants were missing a letter out as they read the longer string. Such results are consistent with findings in observers with normal vision where more errors were made when participants read long rather than short letter strings (Bedell et al., 2015).

The current study showed more crowding in the participants with deeper amblyopia (Figure 6.1). Regan et al. (1992) compared single letter acuity, Snellen acuity and repeat letter acuity in amblyopic children and adults and found most individuals had poorer Snellen (line) than single letter acuity, similar to our findings. They also identified individuals with errors of gaze control, whose repeat letter acuity was better than their Snellen acuity. In the top panel of Figure 6.7, the ratio of repeat letter/Snellen against Snellen acuity (decimal) is plotted for the group of amblyopic adults in Table 5 of Regan et al. (1992). A high value of the repeat letter/Snellen ratio denotes poorer gaze control. Figure 6.7, top panel, shows that individuals identified as having poor gaze control tended to have poorer VA. For comparison, Figure 6.7, bottom panel, shows data from the current study. Normalized logMAR scores were derived from 3 of the tests by subtracting unflanked logMAR from crowded logMAR. These are plotted against logMAR derived from the initial screening. Paired t-tests with Bonferroni correction show that the slopes of these lines are all significantly different to each other ($p<0.01$). These data also show the individuals with deepest amblyopia display most crowding. The steepest slope is from data derived from the line test with letter flankers, LC, showing the strongest relationship between crowding from this test and depth of amblyopia.

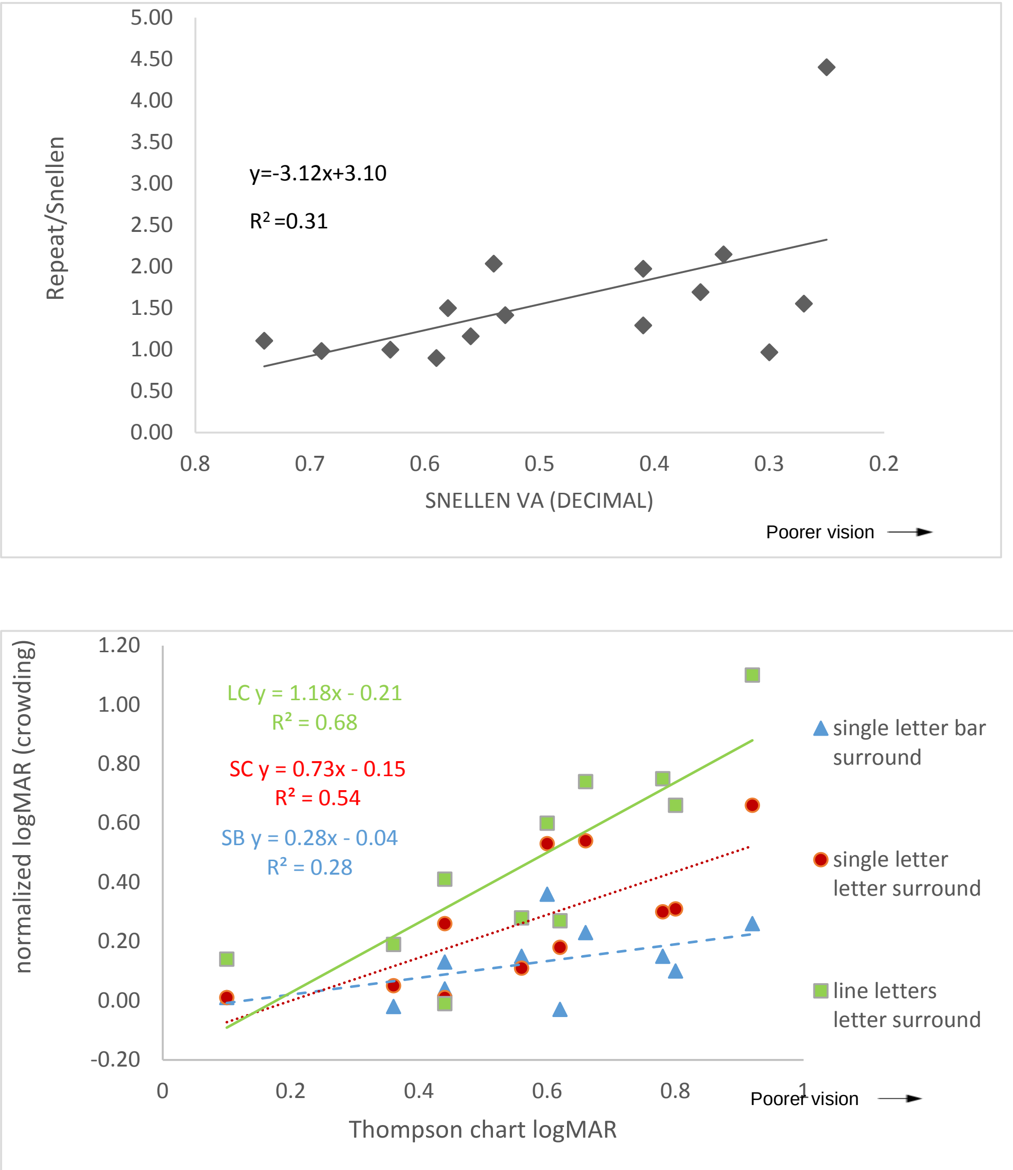


Figure 6.7 The top panel shows data from Regan et al. (1992), plotted from their Table 5. The ratio of repeat letter acuity/Snellen acuity is plotted against Snellen acuity for a group of adult amblyopes. The grey line is the straight line of best fit. The bottom panel shows initial logMAR from screening plotted against logMAR from 3 tests in the current study, normalized to unflanked logMAR, with straight lines of best fit: SB (blue triangles, dashed line), SC (red circles, dotted line) and LC (green squares, solid line)

Greater positional uncertainty (Barbeito et al., 1988) and greater fixational unsteadiness (Schor and Flom, 1975) have been reported with greater depth of amblyopia and Chung et al. (2015) found a correlation between acuity and fixation stability. In the current study, the exact eccentricity of fixation in the amblyopes was not measured. This information may have enabled the relationship between performance of individual amblyopes on the line charts and eccentricity of fixation locus to be explored, although locus of fixation has been found to account for only some of the acuity loss in the amblyopic eyes of strabismics (Kirschen et al., 1981, Kirschen and Flom, 1978).

6.4.4 Effect of attention

Grouping theories of crowding predict that there is more peripheral crowding when the flanker and target are from the same perceptual group i.e. all letters, rather than a target letter with bar flankers (Nazir, 1992, Kooi et al., 1994). Could a similar process be operating in foveal or extra-foveal viewing in strabismics? Fixation in a strabismic child is driven by the non-strabismic eye (Wang et al., 2015). It has been suggested that the strabismic eye may be less able to drive attention because of lower acuity during the critical period impairing the ability of the amblyopic eye to select the target from other distracting information (Wang et al., 2015). In the amblyopic eyes of the strabismic group, poorer mean logMAR was found in the tests with letter flankers rather than bar flankers i.e. logMAR was lower in SC than SB and also lower in LC than LB. Identifying a letter target from among letter flankers represents an increased attention demand compared to identifying a letter among bar flankers. So the poorer performance in LC than LB could be evidence of an attention deficit in these amblyopes. However, it is difficult to separate attention and eye movements, as they are closely linked, with attention determining the location for an eye movement (Flom, 1991, Hoffman and Subramaniam, 1995). The poorer performance in the 7 than 5 letter version of the line test with bar flankers, LB, infers that in LC, the line test with letter flankers, the longer letter string contributes to the poorer performance as well as the greater attention demand caused by the letter flankers, see Bedell et al. (2015).

Eye movements cannot be discounted in a comparison of the single letter tests with bar and letter flankers. For a patient with strabismus and amblyopia given the task of naming the central letter in test SCsl, poor fixation would impair recognition of the target letter, as fixation can drift between letters such that the participant is unsure whether or not he is reading the intended letter. The error analysis of SCsl (Figure 6.5) showed that near threshold, participants were naming the flanking letters at a frequency greater than predicted by chance, but crucially, the proportion of adjacent errors was not greater in amblyopic eyes than fellow eyes, suggesting that poor fixation in the amblyopic eyes is not the main factor in the greater crowding measured in the single letter test with letter flankers. Therefore, our results infer that vision of strabismic amblyopes, like young children, is determined in part by the attention demand in disregarding the nearby objects in favour of the target.

6.4.5 Fellow eyes

Mean logMAR of fellow eyes in this study was good and elevated crowding was not seen in the crowded test conditions. However, it is of interest to compare the error analysis of the fellow eyes in Figure 6.4 with that of the adult participants with normal vision from the study reported in Chapter 4. Figure 4.4 shows adjacent right, adjacent left and random errors for tests LB and LC for two groups of children and adult controls. In LB, the adult controls made mostly random errors with adjacent errors below a level that would be expected by chance. A similar pattern is seen in Figure 6.6 for the fellow eyes of strabismic amblyopes in test LB. Yet, interestingly, a comparison of test LC in Figures 4.4 and 6.6 yields a different pattern. Figure 4.4

shows the adult participants made errors in LC at a level similar to that which would be expected by chance, whereas the fellow eyes of the amblyopic adults (Figure 6.4) made more adjacent errors than would be expected by chance. This comparison infers that the greater attention demand of the letter flankers in the line chart forces ‘letter order’ errors in the fellow eyes of amblyopes but not in normal adult controls.

Previous reports have shown deficits in the fellow eyes of amblyopes in motion perception (Ho et al., 2005, Ho and Giaschi, 2006, Simmers et al., 2003, Giaschi et al., 1992) and contrast sensitivity (Chatzistefanou et al., 2005). On the other hand, oculomotor control in the fellow eye of amblyopes was found to be no different to normal control eyes (Chung et al., 2015), although see Bedell and Flom (1985). The deficits in motion perception imply abnormality in areas of the parietal cortex which contain large numbers of binocular neurones and which mediate visual attention (Ho et al., 2006). Our finding of a potential influence of attention in the fellow eyes of strabismic amblyopes in crowded reading tasks warrants further investigation.

6.4.6 Conclusions and recommendations

These results show that similar to young children, crowding in strabismic and mixed strabismic/anisometropic amblyopic eyes is dependent on stimulus and task demands. The more precise eye movement control required to read a string of letters and the greater attention demand of increased letter-flanker similarity increase crowding in this group. These two factors can have an additive effect with the poorest performance being in the test with linear presentation with letter flankers. More crowding was evident in participants with deeper amblyopia.

Scrutiny of the individual results of participants shows that whilst some show poorer logMAR in the line tests than the single letter tests, not all do. Furthermore, two of the participants with the same logMAR from initial screening (PD and FD) performed very differently across the tests. This variability in results probably reflects the variety of clinical presentation in the group. As well as a range of depth of amblyopia and mixed treatment history, some participants had anisometropia as well as strabismus, whilst others had no anisometropia. Some had a degree of stereopsis, whilst most had none and there was variation in habitual fixation of the participants. To improve detection of amblyopia, my results indicate that, rather than a single visual acuity test, a set of tests could help determine amblyopia type and inform treatment options. Measurement of unflanked logMAR as well as crowded logMAR would enable the depth of crowding to be calculated. In addition, 2 crowded tests could be used, a linear 7 letter test, with letter flankers, like LC, and a single letter test, also with letter flankers, like SC. Most amblyopic participants had poorest scores on the line test with letter flankers, implying high sensitivity as a screening test. For some participants, the difference in crowding between SC and LC was much greater than others. The participants who showed greater difficulty with a linear test compared to a similarly flanked single letter test were presumably those with poorer gaze control. Persistent amblyopia has been linked to poor gaze control (Birch, 2013), so treatment for children showing a large difference between single and linear tests could focus on strategies which minimize the disruption to binocular input (Subramanian et al., 2013)

Chapter 7

Summary and conclusions

7.1 Contribution to knowledge

In this series of experiments, it has been shown that the design of crowded visual acuity tests influences the resulting logMAR. Using custom-designed tests, an effect of both attention and eye movements in crowding has been shown: in both young children and adult strabismic amblyopes, the use of linear rather than single optotypes and use of letter rather than bar flankers has been shown to increase crowding. These two factors have an additive effect, with most crowding resulting from linear letter presentation with letter flankers. A decrease in crowding with age in children has also been shown. Between the ages of 4 and 9, both the extent and magnitude of crowding has been shown to decrease.

The study described in Chapter 2 showed that in commercially available crowded children's visual acuity tests, logMAR was better in the Sonksen logMAR Test than in the logMAR Crowded Test (mean difference 0.07 logMAR), presumably because of the greater inter-optotype spacing and slightly larger distance to the surround box superiorly in the Sonksen Test. Crowding in the Crowded Kay Pictures Test was shown to be less robust than in the crowded letter tests, particularly in older children, probably because of the greater angular separation of the optotypes and surround bar. A decrease in crowding with age was also evident between the ages of 4-6 and 7-9 (mean difference 0.04 logMAR for the letter tests), showing crowded acuity to develop more slowly than single letter acuity.

Chapter 3 described the design and production of a series of visual acuity tests to follow up these results by measuring the relative contributions of various components of crowding. A pilot study demonstrated the effect of length of flanker bar on logMAR.

The second main study, described in Chapter 4, used custom-designed tests to disentangle the contributions of contour interaction, eye movements and attention to the crowding effect. A greater extent of contour interaction was found in children than adults, which was not mature by 9 years and the depth of contour interaction was greater in young children (aged 4-6) than adults. Both linear presentation of letters (showing the effect of eye movements) and use of letter rather than bar surrounds (showing the effect of attention) caused more crowding in the younger children (aged 4-6) than in the older children (aged 7-9) or adults and together, linear presentation and letter surrounds had an additive effect. Error analysis of the linear tests showed that use of letter rather than bar flankers resulted in more errors in the order of letters being read and a greater proportion of backward regressions in young children than adults. Psychometric functions showing mean percent correct against optotype size were plotted for unflanked letters and two of the crowded conditions (Chapter 5). The slopes of the functions increased as more crowding features were introduced. The test with linear presentation and letter flankers had the steepest slope, which infers greater repeatability of such a test over a less crowded one.

The third study (Chapter 6) used custom-designed tests, similar to those in Chapter 4, in a group of strabismic and mixed strabismic/anisometropic amblyopes to infer the relative influence of contour interaction, linear versus single presentation and target-flanker similarity on visual acuity (logMAR) in the amblyopic and fellow eyes. Similar to the group of young children in Chapter 4, the amblyopic eyes showed an elevation of crowding with letter rather than bar flankers and with linear rather than single letter presentations. There was also an additive effect, with highest crowding occurring in the linear presentation with letter flankers. Error analysis showed a pattern of errors in the longer letter strings (when 7 letters were read) that implied letters were being missed out. This happened with greater frequency in the amblyopic eyes than the fellow eyes, inferring an inaccuracy of eye movements. Error analysis of the single letter test with letter flankers showed a pattern of errors similar in amblyopic and fellow eyes, inferring that the poorer performance in the single letter test with letter flankers than the single letter test with bar flankers was a result of the greater attention demand of the letter flankers.

7.2 General Discussion

7.2.1 What makes a good screening test?

A good screening test should be easy to administer, valid and reliable (Herman, 2006). The Bailey-Lovie principles (see section 1.3.2), adopted in the Bailey-Lovie, ETDRS and other charts have led to accurate and reliable visual acuity tests which most adults and children over the age of 6 are able to perform (Bailey and Lovie-Kitchin, 2013, Manny et al., 2003). Some manufacturers of children's tests have adopted the Bailey-Lovie principles rather loosely in their chart designs and a range of tests is commercially available where acuity levels which are nominally the same, comprise optotypes of different height, width, complexity and number of available choices (Bailey and Lovie-Kitchin, 2013). It also appears that children's visual acuity test chart designers have different goals. The Sonksen test was designed to have similar features to the ETDRS chart, but with greater testability than the full ETDRS chart (Salt et al., 2007). This principle has the advantage of longitudinal continuity of visual acuity measurement as children progress onto adult charts. However, the ETDRS test has an inter-optotype spacing of 1 letter width, a separation where there is little, if any, contour interaction in adults (Flom et al., 1963b, Levi, 2008). Should not crowding be exploited in children's acuity charts, knowing that abnormal crowding could reveal strabismic amblyopia (Simons, 1983) and potentially also reading difficulties (Kwon et al., 2007, Atkinson, 1991)? The logMAR Crowded Test (McGraw and Winn, 1993) uses half a letter width spacing to increase the sensitivity of amblyopia detection and has also maintained many of the features of the ETDRS test with logMAR scoring to improve reliability. The Amblyopia Treatment Study Visual Acuity Testing Protocol (Holmes et al., 2001) comprises a single H, O, T or V letter with surround bar at half a letter width. The single letter presentation was chosen for better testability in younger children and the half letter width flanker spacing to increase sensitivity to amblyopia detection (Holmes et al., 2001). The Cambridge Crowded test was designed to improve on the Sheridan Gardiner test and uses letter flankers at half an optotype distance to crowd the target letter (Atkinson et al., 1988). However, this test is not available in logMAR format and there is no published normative data.

7.2.2 Recommendations for design of children's visual acuity tests

Most screening programmes in the UK and abroad use visual acuity as the main means of identifying children who would benefit from a fuller eye examination, yet specificity of visual acuity measurement in detection of amblyopia could be improved (Birch, 2013). The best test to use is one whose results will have greatest difference between the normal and abnormal populations. The results reported in this thesis suggest that a good visual acuity screening test will comprise the following:

- Letter targets with flankers at 0.5 letter widths or closer, to ensure flankers are within the zone of contour interaction
- Letter flankers to increase attention demand
- Linear presentation to reveal disorders of eye movements.
- For children who perform poorly on linear, crowded tests, testing with isolated and single letters crowded with letters, to identify abnormal crowding.

Recent US guidelines for vision screening (Cotter et al., 2015) recommend either auto- or photorefraction or visual acuity testing. Auto- or photorefraction only detects refractive error. Recommended visual acuity tests comprise either single HOTV optotypes or Lea symbols surrounded by crowding bars as best practice and linear presentation with a rectangular surround bar as acceptable practice. Greater testability in young children is the justification for use of single rather than linear presentation as best practice. The report of the Maternal and Child Health Bureau and the National Eye Institute Task Force on Vision Screening (Hartmann et al., 2000), referenced by Cotter, recommends HOTV optotypes or Lea symbols in full chart format or as single surrounded optotypes. The Amblyopia Treatment Study Visual Acuity Testing Protocol (Holmes et al., 2001) uses single HOTV optotypes surrounded by crowding bars, citing a study by Sprague et al. (1989) as evidence to support the rationale for single optotype presentation. The methodology used by Sprague and colleagues involved presentation of a full letter chart to children, with use of a mask to isolate letters when children could not identify 4 of the 6 symbols on a line. The percentage of children who required this isolation of optotypes was used as an indicator of testability of line charts. However a confound is evident here between children for whom the linear task was just too complex and those who were experiencing elevated crowding.

In Sweden, a full HOTV chart is used in vision screening (Kvarnström et al., 2002), whilst in New Zealand, uncrowded Sheridan Gardiner test is used (Anstice et al., 2012). No specific visual acuity tests are recommended for screening in the UK (National Screening Committee, 2013) or Australia (Hopkins et al., 2013). So, whilst the U.S. vision screening guidelines appear to be some of the most specific, there is limited evidence to support the choice of test format. A simple format chosen for high testability may not have the greatest sensitivity and specificity for amblyopia detection. Further studies are indicated.

The recommendations arising from this thesis concur with many of those of Song et al. (2014), who suggest use of letter rather than bar flankers to increase crowding and closer letter-flanker separation than the 1.0 optotype width used in most commercially available tests. In addition, my results also suggest that linear presentation will increase sensitivity to amblyopia detection. Use of linear presentation as well as letter flankers like in my LC (Table 4.1) format has a potential trade-off with testability (Egan and Brown, 1984). Although some authors recommend single optotypes in young children (Keith et al., 1972, Simons, 1983), the literature shows that linear presentation can have good testability in children from 3 years old. The Vision in Preschoolers Study Group (2004) and the Vision in Preschoolers Study Group (2010) found good testability (>95%) of children aged 3-5 with single line crowded HOTV and Lea Symbols tests and Kvarnström and Jakobsson (2005) found around 83% of children age 3 and 96% of children age 4 are able to be tested with same tests. Salt et al. (2007) found over 80% 3 year olds and over 90% 4 year olds able to be tested with the Sonksen logMAR Test (also in single line format).

Very few of the 4-6 year olds in the study reported in Chapter 4 were not able to complete all the testing, but the complex appearance of the linear chart with letter flankers, LC, (Table 4.1), together with the instruction to read only the middle line from left to right could reduce testability in children younger than 4.

7.2.3 Recommendations for scoring of children's visual acuity tests

A strict protocol is required when measuring visual acuity for research purposes and I would also advocate the use of a strict scoring protocol in clinical visual acuity measurement. Participants in my studies were asked to read the linear presentations in order from left to right, but the amblyopic participants had to overcome a temptation to pick out letters which to them were more visible, such as the less crowded end letters. In paediatric clinical practice, the difficulties posed for an amblyopic child reading a linear presentation of letters would be masked if the clinician were to allow the letters to be read in any order and interpret the intended position in the line. A protocol should therefore require children to read the letters in order as presented. Score sheets for a linear children's acuity test could be provided with the test, such as those provided with colour vision tests. The score sheet could contain standardized instructions as well as means to record which letters were read correctly, highlight the termination rule and calculate a logMAR score. There should also be rules to encourage guessing and to prohibit pointing at letters by the clinician in order to improve standardization.

An alternative to manual scoring would be a computer based system, such as that used in the Amblyopia Treatment Study Visual Acuity Testing Protocol (Holmes et al., 2001), the COMPlog System (Laidlaw et al., 2003) or the E-ETDRS test (Beck et al., 2003). Computer based protocols provide quick and accurate results in a consulting room, with the ability for results to be recorded and acuity scores calculated. However, unless they are portable, computer-based systems are less practical if vision screening takes place in schools, or community centres.

7.2.4 Age norms

Monocular and binocular normative data should be available for an ideal crowded children's visual acuity test. Where more crowding features are used to increase the sensitivity to amblyopia detection, the logMAR may be lower than clinicians expect so normative data, perhaps in the format of centile charts, like for example that of the Sonksen Test (Sonksen et al., 2008) will enable sound referral judgements to be made.

7.3 Limitations

Children in my first two studies were recruited from a school population of age 4 and above. Vision screening is often carried out between the ages of 3 and 5, so, although developmental crowding trends in younger children could be deduced from the current data, further research on testability with younger children would be needed before specific test formats could be recommended for this age group.

Because children were tested in their schools, refraction was not performed before testing. In the study described in Chapter 2, children were screened by visual acuity measurement, but data from all children who completed the testing were included. This was done in order to compare measurement across all the VA tests in a population of children. However, if there were more uncorrected myopes in the older group of children (5-8 yrs) than the younger (4-6yrs), an improvement in logMAR over time could be masked. The data were remodelled (section 2.5.9) with the exclusion of 5 participants.

There were enough children in the studies to show statistical significance between tests, but the age groups into which they were divided were fairly broad, which limited the conclusions that could be drawn about age of maturation of acuity with the various tests.

Children in the UK start school between the ages of 4 and 5. The data presented in this thesis show an improvement in crowded acuity in the first 4 years of primary school, which coincides with the years that children are learning and practising reading. If children in other countries learn to read at a different age, then to generalize these findings to other countries may not be valid.

There was variation in crowding amongst the amblyopic participants, although taken as a group, the number of strabismic and mixed strabismic/anisometropic participants was sufficient to show statistically significant differences between single letter and linear presentation (in both bar and letter flanker conditions) and between letter flankers and bar flankers (in both linear and single letter conditions). More amblyopic participants would have enabled analysis between 3 groups of amblyopic participants: anisometropic, strabismic and mixed strabismic/anisometropic. More participants would also enable horizontal and vertical error analysis in tests SCsl and LCsl (Table 6.2).

7.4 Future research

The results presented in this thesis open up possibilities for further research as discussed below:

7.4.1 Testability of a line test with letter or letter-like flankers in pre-school children

There is a challenge in developing a test which maximises the crowding differences between normal and amblyopic children, but presents a task which a 3 year old child will understand and be able to complete. A future study could assess testability and reliability of such a test in comparison with available tests.

7.4.2 Multi-regional study of development of visual crowding

Unflanked and crowded visual acuity could be measured across several cultures where reading skills are taught and practised at different ages. A hypothesis could be that maturation of crowded acuity takes place at an earlier age where children are taught to read earlier.

7.4.3 Repeatability of crowded visual acuity tests

Chapter 5 showed that the psychometric functions derived from tests with more crowding features had steeper slopes than those from tests with fewer or no crowding features. Repeatability could be measured directly in normal and amblyopic eyes with these tests. The hypothesis would be that tests with more crowding features show greater repeatability than those with fewer or no crowding features.

7.4.4 Repeatability of crowded visual acuity tests in amblyopic observers

Flom (1986) derived frequency-of-seeing curves from S-charts in amblyopic and normally sighted observers and found shallower slopes from the amblyopic observers. A further study could use various formats of crowded acuity test in amblyopic observers to compare repeatability across different test formats.

7.4.5 Substitution of a 'dot' flanker in peripheral viewing

In Chapter 3, I was not able to support the hypothesis that a square 'dot' flanker results in more crowding for a Landolt C than a Sloan letter target. This experiment could be repeated in peripheral viewing, where substitution of the 'dot' into the C may occur. The hypothesis would be that in peripheral vision, a square 'dot' flanker results in more crowding for a Landolt C than a Sloan letter target.

7.5 Concluding remarks

Currently available children's crowded visual acuity tests lack standardization and can be chosen and used by clinicians with little appreciation for how or why they differ from each other or what acuity to expect in children of different ages. The results presented in this thesis infer that acuity measured in crowded tests depends on the age of the child, the presence or absence of amblyopia, the inter-optotype separation, the types of optotype used (letter or picture), the type of flanking element (letter, or bar) and the format of optotype presentation (single or linear). As measurement of visual acuity remains the mainstay of children's screening programmes, recommendations are made by which crowding from several test formats could be compared to improve referral of children for appropriate treatment and monitoring of treatment success.

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Chapter 2

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The Sloan font was downloaded from http://psych.nyu.edu/pelli/software.html (Pelli et al., 1988).

Chapter 5

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Student's t-test values to test for the significance of the difference between slopes used the following calculator:

http://www.danielsoper.com/statcalc3/calc.aspx?id=103

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Appendix 1

Abstract: American Academy of Optometry, San Francisco, Nov 2010

CROWDING IN CHILDREN'S VISUAL ACUITY MEASUREMENT: THE IMPORTANCE OF GAZE CONTROL AND CONTOUR INTERACTION

Authors: Yvonne Norgett and John Siderov
Anglia Ruskin University, UK

Crowding features in children's vision tests are necessary to avoid an over-estimation of acuity. However within available tests, the three elements of crowding: contour interaction, gaze control and attention are present to varying degrees. Our aim was to investigate the relative effect of the crowding components on measured acuity.

Monocular, habitual visual acuity was measured in 103 school children, using each of the following tests: logMAR Crowded, Crowded Kay Picture, Sonksen logMAR, Single logMAR Kay Picture and Sheridan Gardiner. Tests were presented in a random order using standardized instructions. For each test, 4 optotypes were presented at each acuity level. Testing continued until 3 or more errors were made at any level. Results were analysed in 2 age groups, younger (4-6 years) and older (7-9 years).

Visual acuity data were converted into logMAR and each correctly read optotype was scored. A one-way, repeated measures ANOVA was performed on the data. In the older children, there was a significant main effect of test on acuity (F=63.59, df=4, p<0.001). An effect of crowding was evident in the two crowded letter tests but not in the crowded picture test. In the younger children there was also a significant main effect of test on acuity (F=63.92, df=4, p<0.001). However, in this group, an effect of crowding was seen in all three crowded tests. In both groups, mean acuity was lowest with the logMAR Crowded Test, (inter-optotype spacing 0.5), slightly higher with the Sonksen Test (spacing 1.0) and highest with the single optotype tests (no crowding).

Our results show that the logMAR Crowded Test which induces contour interaction and requires accurate gaze control gives the lowest measured acuity. The Sonksen Test, despite having more widely spaced letters, still measures lower acuity than a single letter test. This implies that both contour interaction and gaze control are important in visual acuity measurement.

This work was funded in part by a College of Optometrists iPRO Small Grants Award.

Appendix 2

Abstract: American Academy of Optometry Meeting, Seattle, October 24, 2013.

Foveal crowding differs in children and adults

Yvonne Norgett and John Siderov

Anglia Ruskin University, UK

Purpose

Laboratory based studies showed the extent of crowding to be greater in children than adults. This study used custom designed charts in a clinical setting to investigate crowded letter recognition in school children aged 4-9 in a variety of conditions.

Methods

Acuity was compared using charts with bar vs letter flankers to assess the influence of target-flanker similarity and using single letter and linear formats to evaluate the contribution of eye movement control. High contrast Sloan letter charts were presented monocularly on an iPad (Apple inc.) at 4m using standardized instructions. Edge-to-edge separation of letter to flanker was 0.5 letter widths. Five letters of each size were shown and testing continued until 3 letters were named incorrectly. Crowded logMAR was normalized to unflanked logMAR and results were analysed in 3 groups – younger children aged 4-6 (n=32), older children aged 7-9 (n=30) and adult controls (n=27).

Results

Repeated-measures ANOVA revealed that the adults showed no difference in performance in these charts and there was no significant difference in the single letter, bar flanker condition across the groups. Letter flankers and linear presentation individually caused poorer performance in the younger children (mean normalized logMAR 0.17 sd 0.08 in each case) and together had an additive effect (mean 0.24 sd 0.10). Crowding in the older children was adult-like except in the case of a linear presentation with letter flankers (mean normalized logMAR 0.15 sd. 0.08 cf adults mean 0.06 sd.0.06).

Conclusions

These results indicate that both target-flanker similarity and eye movements contribute more to foveal crowding in young children than in adults.

Appendix 3

Abstract: American Academy of Optometry Meeting, Denver, Nov 2014

Effect of crowding on the slopes of the psychometric functions in visual acuity measurements

Yvonne Norgett and John Siderov

Anglia Vision Research

Anglia Ruskin University, UK

Purpose

Clinical measurement of visual acuity involves a determination of a visual threshold. The repeatability of this threshold is likely to be improved if the underlying psychometric function has a steep rather than a shallow slope. The aim of this study was to compare the slopes of psychometric functions derived from measurements of visual acuity in children and adults under different crowding conditions.

Methods

Visual acuity was measured on a group of young children (aged 4-6 yrs., n=32) and an adult control group (n=27) with normal vision using 3 different custom-designed visual acuity charts, comprising high contrast black-on-white Sloan letters presented as uncrowded single letters (uncrowded), single letters flanked with a bar (single flanked) and a line of letters flanked with letters (linear flanked). The charts were presented on an iPad (Apple inc.) and viewed monocularly at 4m. Edge-to-edge separation of letter to flanker was 0.5 letter widths for the 2 crowded charts. For each chart, 5 letters of each size were shown using standardized instructions and testing continued until 3 letters were named incorrectly. Percent correct responses for each letter size were pooled for each group for the 3 chart conditions. The means of the resulting data were separately fit with Weibull functions to derive the psychometric functions.

Results

The slopes of the psychometric functions for the uncrowded, the single flanked and the linear flanked conditions for the children were respectively: 6.6, 9.3 and 10.8 and for the adults: 6.2, 7.1 and 9.3. For both groups, the slopes of the psychometric functions became steeper with increasing crowding features, with the slope of the most crowded chart significantly different from the uncrowded chart in both groups $p<0.05$.

Conclusions

The slopes of the psychometric functions underlying visual acuity measurements become steeper with increasing crowding features for both young children and adults with normal vision, although more so for children. The results suggest that visual acuity measured with charts that have crowding features should be more repeatable and therefore adds further support for the use of crowded visual acuity charts in clinical practice.

Appendix 4 Information letter to parents for study described in Chapter 2

Research Project - The assessment of visual acuity in young children – which test is best?

I am a registered optometrist and lecturer in Optometry at Anglia Ruskin University. I have been awarded a grant by the College of Optometrists (UK) to conduct a study to compare new children's vision charts and recommend which one works best. I am seeking your consent for your child to be included in the study.

A lazy eye in a child may not be obvious to either the child or parents if the other eye is normal, yet if not treated before the age of around 8 years of age, may lead to permanently reduced vision in that eye. Optometrists and other healthcare professionals need tools to test children's vision that are sufficiently sensitive to detect a reasonably small difference in function between the two eyes. Several new vision charts have recently been developed which include features designed to work better than the traditional letter chart.

I shall be coming to your child's school on *date* and spending about ten minutes with each of the eligible children in your child's class. Each child will be asked if they wish to participate in the project. If they agree, I will conduct a number of short tests to measure vision. I will ask them to read letters or recognize symbols on the vision charts we are comparing. Be assured that all of the tests and procedures employed in this research are not experimental and are used in routine practice. The project has been approved by the appropriate Anglia Ruskin University Research Ethics Committee.

The tests which I will be doing are not a full eye examination and do not screen for all abnormalities of the eyes. If however I do suspect a problem with vision in your child's eyes I will send you a letter recommending a full eye examination. Throughout the project your child's name will be protected and confidentiality is ensured.

If you are happy for your child to participate, please sign the enclosed consent form and return to the class teacher by *date*. Participation in the study is voluntary, but your child is likely to find the procedures interesting and fun and they will be contributing to some valuable research.

Thank you for your support. Please contact me if you have any other questions.

Yvonne Norgett BSc(Hons) MCOptom

Contact 0845 196 2671

Email: yvonne.norgett@anglia.ac.uk

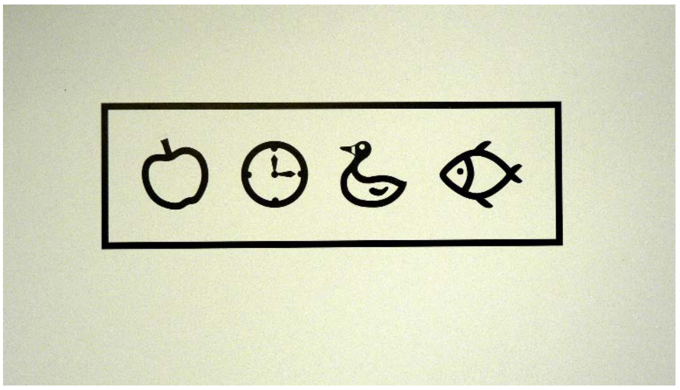
Appendix 5 Information letter to children for study described in Chapter 2

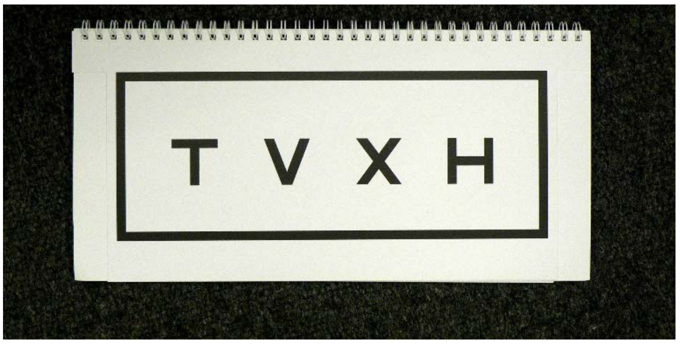
Pupil Information Sheet

Eye Test Chart Project

Hello!

We will be coming to your school soon to test your eyes using letters and pictures. The charts we will use look like this:





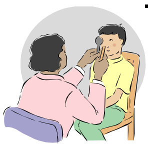
Questions which you may have:

How long will it take?

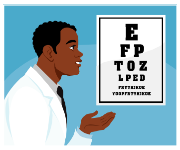
About 5 minutes per child

If I wear glasses, will I have to take them off?

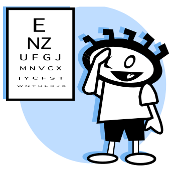
No, the team would like to see what you can see with the help of your glasses.



Who will do the testing? Two optometrists will come along with some university students and can answer any questions you may have.



What will I have to do? You will be asked to read some letters and name some little pictures on charts like the ones in the pictures on the other side. If you are able to see them easily, you may be asked to read some smaller ones.



What happens if I can't see the letters and pictures?

This is usually nothing to worry about. Most children won't be able to read some of the small ones.

Appendix 6 Information letter to parents for study described in Chapter 4

Anglia Ruskin University

Department of Vision and Hearing Sciences

Research Project – Development of Visual Crowding in Children

I am a registered optometrist and lecturer in Optometry at Anglia Ruskin University. I am conducting a study which explores the development of various aspects of children's vision. I am seeking your consent for your child to be included in the study.

'Visual crowding' refers to a normal phenomenon whereby it is more difficult to see an object when it is surrounded by other objects rather than if it is seen in isolation. Some of our earlier research and that of others, has shown that this 'crowding' is greater in younger primary school children than in older children. The goal of our research is to investigate the factors which contribute to crowding and look at how they change with age in normally sighted children. This will help to determine whether an improvement in a child's vision is as a result of treatment or merely an age-related change.

I shall be coming to your child's school on *date* and spending about twenty minutes with each of the eligible children in your child's class. Each child will be asked if they wish to participate in the project. If they agree, I will conduct a number of short tests to measure eye alignment, focussing power and vision. When measuring focussing power I will use a small device that looks like a video camera. The child will be asked to look into the lens of the instrument while the measurement is taken. I will then ask them to read letters or recognize symbols on the vision charts we have designed. The project has been approved by the appropriate Anglia Ruskin University Research Ethics Committee.

The tests which I will be doing are not a full eye examination and do not screen for all abnormalities of the eyes. If however I do suspect a problem with vision in your child's eyes I will send you a letter recommending a full eye examination. Throughout the project your child's name will be protected and confidentiality is ensured.

If you are happy for your child to participate, please sign the enclosed consent form and return to the class teacher by *date.* Participation in the study is voluntary, but your child is likely to find the procedures interesting and fun and they will be contributing to some valuable research.

Thank you for your support. Please contact me if you have any other questions.

Yvonne Norgett BSc(Hons) MCOptom
Contact 0845 196 2671
Email: yvonne.norgett@anglia.ac.uk

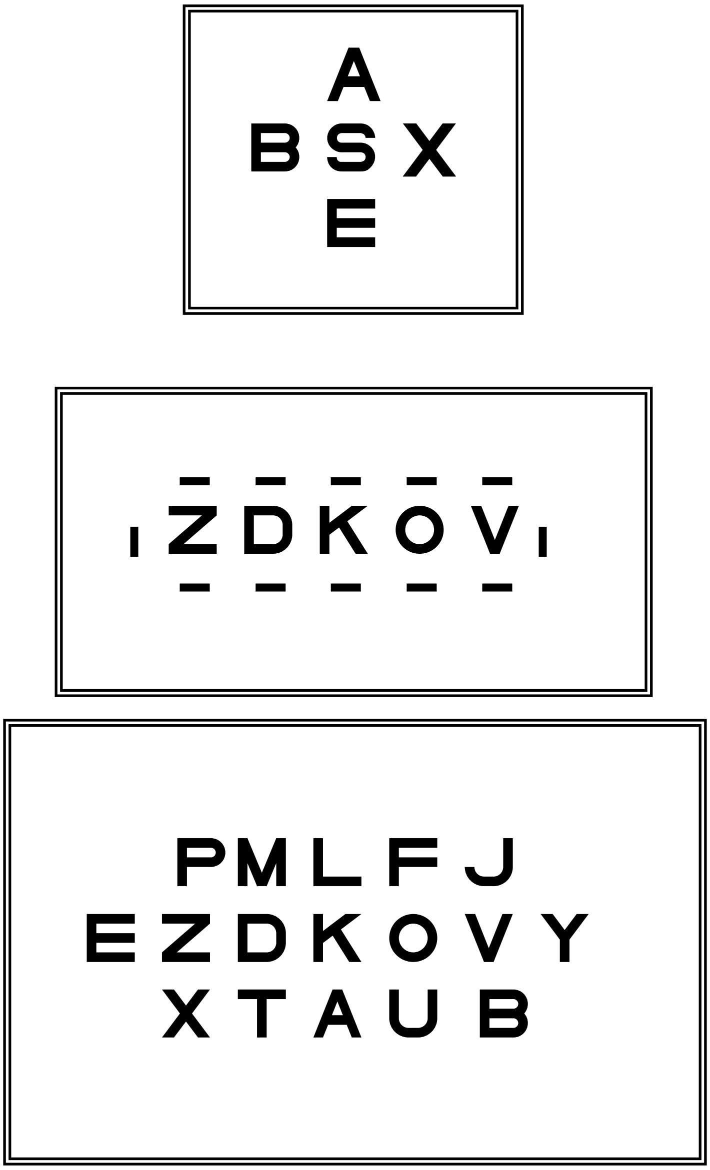
Appendix 7 Information letter to children for study described in Chapter 4

Pupil Information Sheet

Eye Test Chart Project

Hello!

We will be coming to your school soon to test your eyes using letters and pictures. The charts we will use look something like this:



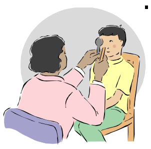
Questions which you may have:

How long will it take?

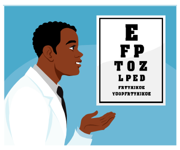
About 20 minutes per child

If I wear glasses, will I have to take them off?

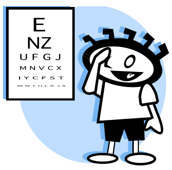
No, the team would like to see what you can see with the help of your glasses.



Who will do the testing? Two optometrists will come along with some university students and can answer any questions you may have.



What will I have to do? You will be asked to read some letters on charts like the ones in the pictures on the other side. If that is hard for you to do, you can point to the letters you see on a card. If you are able to see them easily, you may be asked to read or match some smaller ones.



What happens if I can't see the letters?

This is usually nothing to worry about. Most children won't be able to read some of the small ones.

Appendix 8 Information letter to participants in study described in Chapter 6

Anglia Ruskin University

Department of Vision and Hearing Sciences

Participant information

Research Project: Visual Crowding in Amblyopia (lazy eye)

Optometrists measure vision using a visual acuity chart. This is usually the familiar letter chart with rows of letters of decreasing size. It has been found that it is more difficult to read a letter if it is surrounded by other letters rather than seen on its own. This phenomenon is called visual crowding.

Visual crowding is known to affect the vision of a lazy eye more than an eye with normal vision. I am conducting a research project to identify the best design of visual acuity chart to detect lazy eye in young children. Early detection of this condition gives a child a better chance of early treatment leading to better vision.

As part of my study, I require adults with a lazy eye to look at a series of letter charts displayed on a computer screen. These charts will have letters either presented on their own or in rows. They may also be surrounded by other letters or by lines. The testing will take place in the University Eye Clinic on Bradmore St, Cambridge, just off East Road and should last for around 90 minutes. The maps below show the location of the campus and the University Eye Clinic on the campus.

I would like to invite you to take part in this study. If you are happy to do so, or would like to find out more about the work, please email me on the address below. The data which I collect during the study will form part of my PhD thesis and may be presented at conferences and published in academic journals. Throughout the project, your name will be protected and confidentiality is ensured. The project has been approved by the Faculty of Science and Technology Research Ethics Panel.

If you agree to participate in the study, you will be helping us to better understand the development of amblyopia (lazy eye) and improve its detection in children. These experimental tests are not the same as a full eye examination and can not replace one. I will not carry out any tests which involve contacting your eyes or looking into them. Participation in the project is on a voluntary basis and regrettably, travel or other expenses cannot be refunded.
Thank you for your support

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Appendix 9 Data from chapter 2

age 7-9	Age (months)	LMC	Sonksen	SG	CK	SK
001SG	100	-0.05	-0.2	-0.225	-0.075	-0.075
002AR	95	-0.2	-0.225	-0.225	-0.25	-0.25
003RG	112	-0.05	-0.1	-0.125	-0.15	-0.175
004JMcN	98	-0.05	-0.1	-0.175	-0.175	-0.175
005EB	94	-0.1	-0.1	-0.2	-0.175	-0.225
006JC	102	-0.025	-0.1	-0.175	-0.075	-0.175
007JR	103	-0.05	-0.075	-0.1	-0.15	-0.15
008CT	97	0	-0.2	-0.175	-0.125	-0.275
009AS	105	-0.2	-0.175	-0.225	-0.2	-0.25
010FS	95	0.05	0	-0.15	-0.25	-0.15
011AMcL	106	-0.075	-0.175	-0.25	-0.2	-0.1
012ML	112	-0.1	-0.2	-0.275	-0.3	-0.25
013SH	114	-0.05	-0.15	-0.15	-0.175	-0.225
014AK	98	-0.125	-0.175	-0.225	-0.225	-0.2
015JC	94	-0.175	-0.175	-0.15	-0.225	-0.1
016EP	107	0	-0.05	-0.25	-0.175	-0.175
017PC	104	-0.025	-0.125	-0.225	-0.225	-0.2
018CC	98	-0.025	-0.2	-0.25	-0.2	-0.2
019EP	97	-0.15	-0.1	-0.225	-0.1	-0.225
020AW	97	0.05	0.025	0.075	-0.125	0.025
021JP	103	-0.1	-0.175	-0.3	-0.175	-0.275
022JS	100	-0.075	-0.1	-0.225	-0.175	-0.275
023SB	113	0	0	-0.075	-0.15	-0.2
024AB	109	0.025	-0.125	-0.275	-0.15	-0.25
025RN	108	-0.025	-0.15	-0.2	-0.15	-0.125
026OS	93	0.025	-0.1	-0.175	-0.125	-0.1
027GB	108	-0.05	-0.125	-0.225	-0.275	-0.275
028CB	105	-0.1	-0.25	-0.25	-0.2	-0.25
029GO	112	-0.1	-0.2	-0.225	-0.225	-0.25
030DJ	112	-0.1	-0.075	0.2	0.15	0.225
031HN	101	-0.05	-0.125	-0.225	-0.275	-0.225
032AY	93	0.05	-0.125	-0.2	-0.125	-0.125
033RT	112	-0.05	-0.1	-0.225	-0.225	-0.225
034GT	95	-0.025	-0.175	-0.175	-0.3	-0.275
035SS	110	-0.15	-0.1	-0.275	-0.35	-0.275
036KM	112	-0.15	-0.2	-0.2	-0.2	-0.275
037ZN	95	0.075	-0.1	-0.25	-0.175	-0.225
038CS	110	-0.075	-0.15	-0.2	-0.25	-0.25
039MT	99	0.025	-0.15	-0.175	-0.15	-0.15
040EW	110	-0.075	0	0.2	-0.05	0.025
041KS	96	-0.025	-0.15	-0.15	-0.2	-0.225
042JM	95	0.3	0.225	0.2	0.075	0.1
043TP	96	-0.15	-0.2	-0.25	-0.25	-0.225
044RMcG	102	-0.175	-0.125	-0.225	-0.2	-0.275
045GL	106	0	-0.125	-0.225	-0.25	-0.225
046SL	100	-0.125	-0.25	-0.275	-0.225	-0.225
047OH	110	-0.075	-0.2	-0.225	-0.3	-0.2
048MHT	111	-0.1	-0.225	-0.25	-0.325	-0.275
049ML	108	-0.075	-0.15	-0.2	-0.2	-0.225
050RC	107	0.15	0.1	0.15	0	-0.05
051JH	107	-0.05	-0.075	-0.225	-0.225	-0.25
052SC	116	-0.25	-0.15	-0.225	-0.2	-0.2
053EC	105	-0.05	-0.1	-0.25	-0.25	-0.225
054MC	98	0.075	-0.15	-0.25	-0.075	-0.225
055RH	103	-0.075	-0.125	-0.25	-0.225	-0.25
056MG	113	0.075	-0.125	-0.15	-0.15	-0.2
057HHM	104	-0.05	-0.1	-0.25	-0.15	-0.275
058KB	101	0.025	-0.175	-0.2	-0.3	-0.275
059MF	100	0.1	0.025	-0.15	-0.2	-0.15
060OC	98	-0.075	-0.2	-0.225	-0.2	-0.225
061RW	110	0.425	0.375	0.375	0.3	0.375
062HH	94	-0.1	-0.2	-0.275	-0.325	-0.275
063CM	108	0.125	0.075	0.075	0.05	0.225
064ImcN	114	-0.025	-0.15	-0.2	-0.2	-0.275
mean		**-0.038**	**-0.114**	**-0.169**	**-0.175**	**-0.178**
sd		0.108	0.105	0.135	0.110	0.129

age 4-6	Age (months)	LMC	Sonksen	SG	CK	UCK
065JE	60	-0.075	-0.1	-0.225	-0.05	-0.2
066SC	58	-0.025	-0.1	-0.175	-0.15	-0.2
067TC	64	0.075	-0.125	-0.225	-0.175	-0.2
068CRC	63	0.1	-0.1	-0.175	-0.125	-0.075
069AAA	66	0.075	0.025	-0.05	-0.025	0.175
070KS	62	0	0.05	-0.025	0.05	0.075
071AT	58	0.1	0.075	-0.025	0	0.05
072HS	64	-0.025	-0.15	-0.225	-0.075	-0.075
073LS	62	0.075	-0.125	-0.125	-0.05	-0.05
074CA	60	0.075	-0.025	-0.2	-0.125	-0.225
075AH	63	0.05	-0.05	-0.25	-0.175	-0.25
076MR	67	0.05	0.075	-0.225	-0.05	-0.15
077ES	65	0.075	-0.05	-0.15	-0.075	-0.125
078JB	72	-0.175	-0.225	-0.225	-0.2	-0.275
079AC	66	0.025	-0.1	-0.2	-0.15	-0.225
080PB	68	0.075	-0.05	-0.225	-0.025	-0.2
081EL	77	0.025	-0.075	-0.225	-0.125	-0.175
082TF	70	0	-0.1	-0.175	-0.2	-0.075
083EH	70	0	-0.1	-0.2	-0.15	-0.25
084BM	72	-0.1	-0.1	-0.225	-0.2	-0.225
085RL	66	0.025	-0.025	-0.125	0.025	-0.1
086AOM	65	0.15	0.125	0	0.175	0
087DM	76	0	0.025	-0.125	-0.125	-0.125
088OW	68	-0.05	-0.1	-0.275	-0.175	-0.225
089CS	70	-0.05	-0.175	-0.25	-0.075	-0.2
090DP	69	0.175	0.05	-0.1	0	-0.025
091JS	81	-0.175	-0.275	-0.275	-0.275	-0.275
092CC	80	-0.175	-0.2	-0.275	-0.225	-0.225
093LC	79	-0.025	-0.05	-0.2	-0.125	-0.2
094MMcN	75	0.05	0	-0.075	-0.125	-0.125
095MW	77	-0.05	0	-0.2	-0.15	-0.2
096PS	78	0.025	-0.025	-0.025	-0.025	-0.225
097KH	76	-0.05	-0.025	-0.125	-0.175	-0.2
098RP	76	-0.1	-0.175	-0.2	-0.225	-0.175
099RMcG	72	-0.075	0	-0.225	-0.1	-0.25
100CC	71	-0.075	-0.15	-0.2	-0.175	-0.2
101EN	71	0.075	-0.05	-0.175	-0.075	0
102YG	74	0.025	-0.15	-0.2	-0.025	-0.1
103HW	77	0	-0.2	-0.25	-0.125	-0.275
Mean		**0.003**	**-0.071**	**-0.176**	**-0.104**	**-0.149**
sd		0.083	0.090	0.075	0.089	0.106

Appendix 10 Data from chapter 4

adults	S_0	$SB_{0.25}$	$SB_{0.5}$	$SB_{1.0}$	$SB_{1.5}$	$LB_{0.5}$	$SC_{0.5}$	$LC_{0.5}$
001NK	-0.20	0.06	0.03	-0.11	-0.12	-0.05	-0.08	-0.06
002TS	-0.07	0.08	-0.05	-0.05	-0.11	0.06	0.02	0
003HW	-0.1	-0.03	-0.09	-0.07	-0.12	-0.06	-0.11	-0.12
004LP	-0.02	0.17	0.04	0.01	0.05	0.05	0.01	0.02
005MN	0.02	0.1	0.04	0.01	0.02	0	-0.04	0.09
006EJ	-0.2	-0.07	-0.14	-0.17	-0.26	-0.12	-0.11	-0.08
007JH	-0.09	0.02	0.01	-0.07	-0.06	-0.09	0.01	-0.11
008RN	-0.11	-0.07	-0.09	-0.05	-0.14	-0.08	-0.02	-0.08
009DG	-0.04	0.10	-0.08	-0.08	-0.11	-0.07	-0.05	-0.09
010JR	-0.32	-0.22	-0.18	-0.3	-0.3	-0.28	-0.26	-0.24
011JT	-0.25	-0.13	-0.21	-0.24	-0.32	-0.25	-0.25	-0.26
012NT	-0.34	-0.2	-0.22	-0.36	-0.3	-0.26	-0.27	-0.24
013AE	-0.18	0.14	-0.08	-0.1	-0.12	-0.03	-0.01	-0.01
14CF	-0.32	-0.12	-0.14	-0.28	-0.26	-0.17	-0.22	-0.21
15SW	-0.16	-0.05	-0.11	-0.2	-0.23	-0.09	-0.1	-0.1
016MG	-0.13	0.03	-0.01	-0.14	-0.10	-0.03	0	-0.07
017ST	-0.23	-0.06	-0.16	-0.21	-0.19	-0.09	-0.11	-0.17
018TS	-0.29	-0.1	-0.11	-0.23	-0.27	-0.12	-0.19	-0.14
019AB	-0.2	-0.06	-0.07	-0.06	-0.2	-0.1	-0.11	-0.18
020IP	-0.13	-0.07	-0.14	-0.21	-0.22	-0.14	-0.13	-0.12
021MK	-0.12	0.02	-0.05	-0.02	-0.17	-0.02	-0.07	-0.08
022LM	-0.1	-0.04	-0.08	-0.15	-0.16	-0.06	-0.03	-0.03
023AS	-0.24	-0.05	-0.15	-0.2	-0.24	-0.11	-0.16	-0.18
024MC	-0.28	-0.06	-0.15	-0.24	-0.2	-0.16	-0.15	-0.15
025AS	-0.33	-0.09	-0.25	-0.29	-0.25	-0.21	-0.21	-0.19
025JS	-0.24	-0.05	-0.11	-0.18	-0.24	-0.17	-0.13	-0.14
026EO	-0.20	-0.06	-0.11	-0.16	-0.22	-0.13	-0.14	-0.16
mean	**-0.19**	**-0.03**	**-0.10**	**-0.16**	**-0.19**	**-0.11**	**-0.11**	**-0.12**
sd	**0.10**	**0.09**	**0.08**	**0.10**	**0.09**	**0.09**	**0.09**	**0.08**

age 4-6	S_0	$SB_{0.25}$	$SB_{0.5}$	$SB_{1.0}$	$SB_{1.5}$	$LB_{0.5}$	$SC_{0.5}$	$LC_{0.5}$
105OU	0.02	0.20	0.12	0.13	0.06	0.29	0.19	0.4
125LP	0.1	0.22	0.1	0.16	0.19	0.23	0.2	0.29
127TP	-0.05	0.26	0.1	0.08	0	0.12	0.2	0.19
128FC	-0.2	-0.03	-0.04	-0.05	-0.19	0.05	0.05	0.02
102EH	0.05	0.21	0.13	0.18	0.02	0.17	0.19	0.21
106HM	-0.10	0.06	0.06	-0.02	-0.12	0.05	0.01	0.2
108HT	0.09	0.23	0.21	0.11	0.13	0.24	0.25	0.32
117DE	-0.02	0.25	0.12	0.03	0.04	0.17	0.15	0.21
120MP	-0.1	0.08	0.05	-0.03	-0.09	0.19	0.21	0.34
107AB	-0.08	0.08	0.02	-0.03	0.02	0.01	0.09	0.1
119ZWW	-0.17	0.09	0.01	-0.04	-0.13	0.05	-0.02	0.09
104LR	-0.09	0.08	0.01	-0.06	-0.11	0.25	0.13	0.3
118RL	0.04	0.13	0.08	0.09	-0.08	0.11	0.17	0.12
101AC	0.00	0.14	0.10	0.01	0.03	0.07	0.1	0.14
103SQ	-0.22	0.10	-0.01	-0.09	0.02	0.11	0.1	0.26
109CO	0.00	0.18	0.10	0.06	0.01	0.15	0.19	0.26
111RL	0.1	0.18	0.1	0.06	-0.01	0.08	0.22	0.2
121EC	-0.15	0.01	-0.05	-0.07	-0.15	-0.05	0.05	0.06
129AT	-0.11	0.06	0.08	-0.02	-0.05	0.02	0.05	0.15
124TS	-0.3	-0.02	-0.04	-0.09	-0.12	-0.04	-0.05	0.03
112IJ	-0.1	0.04	-0.12	-0.04	0.01	0.1	-0.05	0.05
115TI	-0.15	0.01	-0.03	-0.11	-0.09	0	-0.04	0.05
123HP	-0.01	0.18	0.13	-0.03	0.02	0.14	0.34	0.26
132WO	-0.26	0.03	-0.03	-0.06	-0.16	-0.05	-0.01	-0.01
116BM	-0.08	0.13	0.07	0	-0.06	0	0.13	0.14
126JD	-0.21	-0.01	-0.06	-0.08	-0.14	-0.01	-0.03	-0.03
110PW	-0.04	0.02	-0.02	0.02	-0.13	-0.05	-0.01	0.03
113CL	-0.14	0.07	-0.1	-0.15	-0.19	0	-0.03	0
122MM	-0.15	-0.04	-0.08	-0.21	-0.19	-0.06	-0.04	0.01
114IT	-0.09	0	-0.01	-0.03	-0.12	0.06	0.04	0.11
131HP	-0.24	0.05	-0.02	-0.14	-0.18	-0.05	-0.11	0.01
130 TS	-0.17	0.06	-0.04	-0.08	-0.13	-0.06	-0.1	0.01
mean	**-0.09**	**0.10**	**0.03**	**-0.02**	**-0.06**	**0.07**	**0.08**	**0.14**
sd	**0.11**	**0.09**	**0.08**	**0.09**	**0.10**	**0.10**	**0.11**	**0.12**

age7-9	S_0	$SB_{0.25}$	$SB_{0.5}$	$SB_{1.0}$	$SB_{1.5}$	$LB_{0.5}$	$SC_{0.5}$	$LC_{0.5}$
225KG	-0.12	0.11	0.06	0.01	-0.07	0.08	0.02	0.09
227IH	-0.13	-0.05	-0.06	-0.15	-0.16	-0.07	-0.08	0.03
226ZP	-0.12	0.06	-0.04	-0.09	-0.09	0.06	-0.02	0.06
224ACK	-0.27	-0.09	-0.15	-0.20	-0.20	-0.12	-0.15	-0.12
211NW	-0.22	0.16	-0.08	-0.18	-0.18	-0.05	-0.09	-0.06
221LS	-0.24	-0.05	-0.13	-0.08	-0.19	-0.07	-0.08	-0.05
228DB	-0.23	0.03	-0.11	-0.16	-0.19	-0.08	-0.07	0.09
230JBM	-0.11	0.06	-0.01	-0.06	-0.15	-0.03	-0.04	0
219GB	-0.23	0.01	-0.03	-0.13	-0.19	-0.09	-0.08	-0.08
223AC	-0.12	-0.02	-0.05	-0.10	-0.15	-0.02	-0.11	-0.01
229PM	-0.20	-0.04	-0.13	-0.08	-0.14	-0.08	-0.11	-0.11
218TL	-0.05	0.00	-0.04	-0.07	-0.07	-0.08	0	0.1
220AJ	-0.28	-0.09	-0.02	-0.25	-0.22	-0.01	-0.13	-0.01
222PW	-0.14	0.03	-0.04	-0.11	-0.12	0.01	-0.01	-0.05
202JSH	-0.25	0.01	-0.08	-0.15	-0.22	-0.07	-0.09	0
207SK	-0.21	-0.05	-0.15	-0.20	-0.17	-0.11	-0.13	-0.08
205SF	-0.09	0.02	-0.05	-0.08	-0.13	-0.06	-0.05	0.04
201LK	-0.27	-0.05	-0.19	-0.21	-0.26	-0.25	-0.23	-0.24
216GS	-0.23	-0.01	-0.1	-0.12	-0.14	-0.07	-0.02	0.1
210WD	-0.06	0.05	0.00	-0.04	0.00	-0.01	-0.05	0.08
204KV	-0.05	0.09	-0.02	-0.02	-0.06	0.03	0.03	0.13
212NR	-0.2	-0.08	-0.13	-0.2	-0.19	-0.12	-0.18	-0.18
209SM	-0.17	-0.03	-0.09	-0.14	-0.18	-0.09	-0.09	-0.02
200OW	-0.16	-0.01	-0.10	-0.13	-0.16	-0.08	-0.08	-0.08
214DM	-0.19	0.04	-0.07	-0.11	-0.17	-0.04	-0.01	-0.04
217RW	-0.04	0.04	-0.04	-0.15	-0.1	0.03	-0.08	0.08
203JB	-0.06	-0.07	-0.07	-0.17	-0.20	-0.13	-0.11	-0.13
206OR	-0.12	0.04	-0.06	-0.11	-0.12	-0.05	-0.05	-0.02
208CG	-0.15	0.14	0.04	-0.01	-0.11	-0.04	-0.08	-0.06
213SG	-0.03	0.06	0.07	-0.04	-0.06	0.06	0.1	0.18
215ED	-0.24	0.02	-0.12	-0.17	-0.17	-0.06	-0.11	-0.08
mean	**-0.16**	**0.01**	**-0.06**	**-0.12**	**-0.15**	**-0.05**	**-0.07**	**-0.01**
sd	**0.08**	**0.06**	**0.06**	**0.06**	**0.06**	**0.07**	**0.06**	**0.10**