ANGLIA RUSKIN UNIVERSITY

FACULTY OF SCIENCE AND TECHNOLOGY

MEASURES OF VISUAL ACUITY, CONTOUR INTERACTION AND CROWDING WITH CONTRAST-MODULATED OPTOTYPES IN ADULTS AND CHILDREN

SARAH LALOR

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ABSTRACT

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WHAT IS THE BEST VISUAL ACUITY TEST FOR CHILDREN?

SARAH LALOR

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The presence of ‘crowding’ features on visual acuity tests for young children are considered important for detecting amblyopia, early treatment of which is key to success. The optimum placement of ‘crowding’ features has not previously been investigated, nor has the change in magnitude of crowding with age been measured with such stimuli. Recently, contrast-modulated noise (CM) stimuli have been suggested to be potentially more sensitive to amblyopia, than standard black on white, or luminance (L) stimuli. CM stimuli also result in larger magnitudes of crowding in normal adults, but this has not been tested in children, or in adults with child-friendly CM optotypes. The first study of this thesis shows that placement of features surrounding the target optotype provide more consistent crowding across symbols, pictures and letters, when separation is specified in units of stroke width, as opposed to units of optotype width. Steeper slopes of the underlying psychometric functions, and thereby increased sensitivity, are produced by placing contour interaction or crowding features near to 1 (one) stroke width away. This separation also maximises contour interaction and crowding. In normal adults, the magnitude of contour interaction is smaller than that of crowding with L and LM, but not with CM, stimuli. The second study of this thesis shows that visual acuity develops more slowly, and becomes adult-like later with CM, compared to L and LM (luminance-modulated noise) stimuli. The magnitude of contour interaction is similar for L, LM and CM stimuli and varies very little across age group (3 to 16 years old and adults). Crowding is larger than contour interaction with L and LM, but not CM stimuli in binocularly normal participants; this is not the pattern of results found in very young children or in binocularly anomalous adults. A comparison of ‘equivalent ages’ for binocularly abnormal adults finds that CM crowded acuity predicts an earlier arrest of normal development, than do L or LM crowded, or any of the isolated optotype acuities.

Key words: visual acuity; crowding; contour interaction; paediatric vision; contrast-modulated optotypes; amblyopia

Contents

List of Figures

List of Tables

Chapter 1

Literature review

1.1 Introduction

Amblyopia is a common developmental disorder of spatial vision affecting 3.5% of adults (Flom and Neumaier, 1966; Attebo et al., 1998; Flynn et al., 1998, 1999; Robaei et al., 2006; Williams et al., 2008) or more (Elflein et al., 2015) and is characterised by reduced visual acuity in an otherwise healthy eye, even with full optical correction (Cole, 1959; Flom and Neumaier, 1966; Attebo et al., 1998; Eibschitz-Tsimhoni et al., 2000; Chua and Mitchell, 2004; Simons, 2005; de Koning et al., 2013).

Amblyopia is thought to be due to the disruption of the normal development of binocular vision in early life (Wiesel and Hubel, 1963; Rauschecker and Singer, 1981; Crawford et al., 1983; Horton and Stryker, 1993; Wensveen et al., 2001; Zhang et al., 2003; Conner et al., 2007; Joly and Frankó, 2014). The most common causes of this disruption are anisometropia, defined as a significant difference in refractive error between the two eyes, and strabismus, defined as ocular misalignment. Although other risk factors exist, such as congenital cataracts or ptosis which result in deprivational amblyopia, this type of amblyopia is outside the scope of this thesis. As well as a loss of visual acuity, amblyopia results in reduced stereopsis (Goodwin and Romano, 1985; Simmers et al., 1999) and reduced contrast sensitivity, especially at higher spatial frequencies (Levi and Harwerth, 1977; Thomas, 1978; Bradley and Freeman, 1981; Howell et al., 1983; Abrahamsson and Sjöstrand, 1988; McKee et al., 2003; Huang et al., 2007). More recently, research has suggested that anisometropic amblyopia and strabismic amblyopia produce fundamentally different spatial deficits (Levi and Klein, 1982; Hess et al., 1983; Levi and Klein, 1985; Levi et al., 1987; Formankiewicz and Waugh, 2013; Levi et al., 2015).

Early treatment of amblyopia is widely believed to be key to success (Epelbaum et al., 1993; Flynn et al., 1998, 1999; Wu and Hunter, 2006). Diagnosis of amblyopia is necessary for treatment to be initiated, therefore early diagnosis is important. Consequently, detection of amblyopia is a key reason for pre-school vision screening (Friendly, 1978; Williams et al., 2002; U.S. Preventative Services Task Force, 2004; Kemper et al., 2005; Bodack et al., 2010; de Koning et al., 2013) which has led to its consideration when designing pre-literate visual acuity charts. Visual acuity for a target optotype measured with surrounding features (such as flanking bars, letters, or a surrounding box) is worse than that measured when isolated (Flom, Weymouth and Kahneman, 1963; Hess and Jacobs, 1979; Leat et al., 1999; Formankiewicz and Waugh, 2013). This negative spatial interaction effect on target resolvability is generally referred to as "crowding", or as "contour-interaction" when referring purely to adjacent contours. Crowding features are used on pre-literate acuity charts, most commonly in the format of a box or four bars surrounding either an individual optotype or a line of four or five optotypes. Crowded charts are recommended for children's vision screening programs (Solebo et al., 2013; Cotter et al., 2015) because it is widely believed that the magnitude of acuity degradation due to crowding is greater for people with amblyopia (Stuart and Burian, 1962; Giaschi et al., 1993; Hess et al., 2001) and therefore the inclusion of crowding features will increase the sensitivity of the charts.

In the following sections, amblyopia diagnosis and treatments will be reviewed along with specific focus being made about the design of children's acuity charts and the presence of crowding features. Potential benefits of using contrast-modulated noise acuity charts for the detection of amblyopia will then be discussed, followed by stating the aims of this project.

1.2 Amblyopia

Amblyopia is most commonly associated with childhood strabismus and/or anisometropia (Attebo et al., 1998). Strabismus, which causes the images in each eye to fall on non-corresponding retinal points (von Noorden and Campos, 2002), and anisometropia, which results in a clearer image forming in one eye than the other eye (Malik et al., 1968) are fundamentally very different visual conditions. However, there is evidence of little or no emmetropisation taking place in the non-fixing eye of humans with strabismic amblyopia (Lepard, 1975; Sireteanu et al., 1981; Birch and Swanson, 2000) and in monkeys with experimentally induced strabismic amblyopia (Kiorpes and Wallman, 1995). There is also longitudinal evidence of strabismus developing in children with anisometropic amblyopia (Birch and Swanson, 2000).

Neural suppression is indicated by the absence of perceived diplopia in strabismus (Sireteanu et al., 1981) and amblyopia being more common in unilateral than alternating strabismus (Harwerth et al., 1983). There is conflicting evidence regarding the correlation between severity of amblyopia (more severe being defined as a larger inter-ocular difference in visual acuity and poorer stereopsis) and depth of suppression with evidence of both an inverse (Harwerth et al., 1983) and positive (Sireteanu et al., 1981; Agrawal et al., 2006; Li et al., 2004; Narasimhan et al., 2012; Li et al., 2013; Chima et al., 2016) correlation.

Some experimental studies using animals provide in-depth information about amblyopia. The effect of monocular deprivation on the development of the visual cortex was investigated by Wiesel and Hubel (1963, 1965) who sutured shut one eye in kittens. At three months of age, very few cortical cells could be driven by the deprived eye. This shows that monocular deprivation early in life can adversely affect the development of the cortical pathways associated with the deprived eye, in a way that is consistent with the deficits seen in amblyopia. A similar study was done by Rauschecker and Singer (1981), with kittens which were tested after four to seven weeks of unrestricted vision in one eye and vision restricted to vertical contours using cylindrical lenses in the other eye, after being raised in the dark for the first four to six weeks. Binocularity was common in neurons preferring vertical orientations whereas neurons preferring non-vertical orientations were dominated by the eye which had unrestricted vision. Monocular deprivation early in life therefore adversely affects the development of binocularity.

Harwerth et al. (1991) psychophysically tested the vision of rhesus monkeys; five monkeys were binocularly deprived from birth, two were monocularly deprived and eight were control monkeys. The spatial contrast sensitivity deficits were so severe in the monocularly deprived monkeys that they could not be measured and the full-field temporal contrast sensitivity functions were substantially reduced, compared to the control monkeys. The binocularly deprived monkeys had spatial and temporal contrast sensitivity functions which were not significantly different ($p>0.05$) from the control monkeys. This is consistent with amblyopia being associated with reduced monocular vision in early childhood, resulting in reduced monocular contrast sensitivity.

Suggestions that the severity of amblyopia can be reduced by brief periods of corrected binocular vision were tested by Wensveen et al. (2006) in monkeys. Uninterrupted binocular vision for one hour a day reduced the severity of amblyopia by 65%, two hours a day reduced the severity of amblyopia by 90% and four hours preserved near normal spatial contrast sensitivity.

Although animal research remains useful for investigating causality and the neural basis of amblyopia, most of these studies use complete monocular deprivation to investigate amblyopia which is different from the more common strabismic and anisometropic forms of amblyopia in humans (Barrett et al., 2004). It is assumed that the cause of the amblyopia is known to be strabismus in cases where strabismus has been artificially induced. However, the ocular immobilisation and trauma from surgical intervention could be causing the amblyopia rather than the ocular misalignment itself (Movshon and Sluyters, 1981; Harwerth et al., 1983). Early form deprivation that causes amblyopia is also capable of causing strabismus, suggesting that the strabismus could be an effect of, rather than the cause of, the amblyopia. Consequently, whilst animal studies can be extremely useful for investigating amblyopia, such studies have their limitations.

1.3 Age of treatment

Amblyopia is thought to be due to the disruption of the normal development of binocular vision early in life (Hess and Baker, 1984; Teller and Movshon, 1986) caused by monocular deprivation, normally associated with anisometropia and/or strabismus (Attebo et al., 1998). Direct experimentation on animals by Hubel and Wiesel (1970) indicated that for monocular deprivation to alter the development of the visual cortex, it had to occur early in life. They termed the period during which abnormal experience could alter normal development the “critical period”. It has been suggested that therapeutic measures may need to take place during this period in order for treatment to be successful, however the term “critical period” refers specifically to the period during which deprivation is effective (Daw, 1998).

The traditional treatment for amblyopia is occlusion therapy which involves covering or blurring the non-amblyopic eye with the intention of encouraging the brain to pay attention to the amblyopic eye. This idea was described by George Louis Leclerc, Conte De Buffon (1707-1788) in 18th Century European literature (Awan, 2008). More recently, binocular anti-suppression treatments, normally game-based, have been developed (Cleary et al., 2009; Polat et al., 2009; Hess et al., 2010; To et al., 2011; Bayliss et al., 2012; Jeon et al., 2012; Li et al., 2012; Foss et al., 2013; Li et al., 2014, 2015; Bach, 2016). The results of these studies are promising, however randomised control trials are required to fully evaluate safety and efficacy (Tailor et al., 2015).

Although there is evidence of successful amblyopia treatment in adults (Mintz-Hittner and Fernandez, 2000; Scheiman et al., 2005; Hess et al., 2010; Astle et al., 2011; Li et al., 2011) there is strong support for the theory that earlier initiation of treatment substantially increases the chance of success (Wick et al., 1992; Flynn et al., 1998, 1999). Strong support for this theory comes from Flynn et al. (1998, 1999) who analysed data from numerous studies published on occlusion therapy for amblyopia between 1965 and 1994, to investigate the factors most important for determining the likelihood of successful treatment. There were 987 amblyopes in total across the combined studies. In conclusion, early initiation of treatment and better initial visual acuity were the most important factors in determining likelihood of treatment success (defined as their visual acuity in their amblyopic eye achieving 6/12 or better after treatment). Figure 1.1 shows their findings regarding the relationship between age at which treatment was initiated, visual acuity before the initiation of treatment and the percentage of participants where treatment was deemed to be successful. However, there is evidence that even after successful amblyopia treatment, recurrence of amblyopia occurs in approximately 30% of patients (Levartovsky et al., 1995; Pediatric Eye Disease Investigator Group, 2005; Bhola et al., 2006). This risk increases if treatment is stopped abruptly (Pediatric Eye Disease Investigator Group,

2005) but is lower if commenced after 10 years of age (Levartovsky et al., 1995; Bhola et al., 2006).

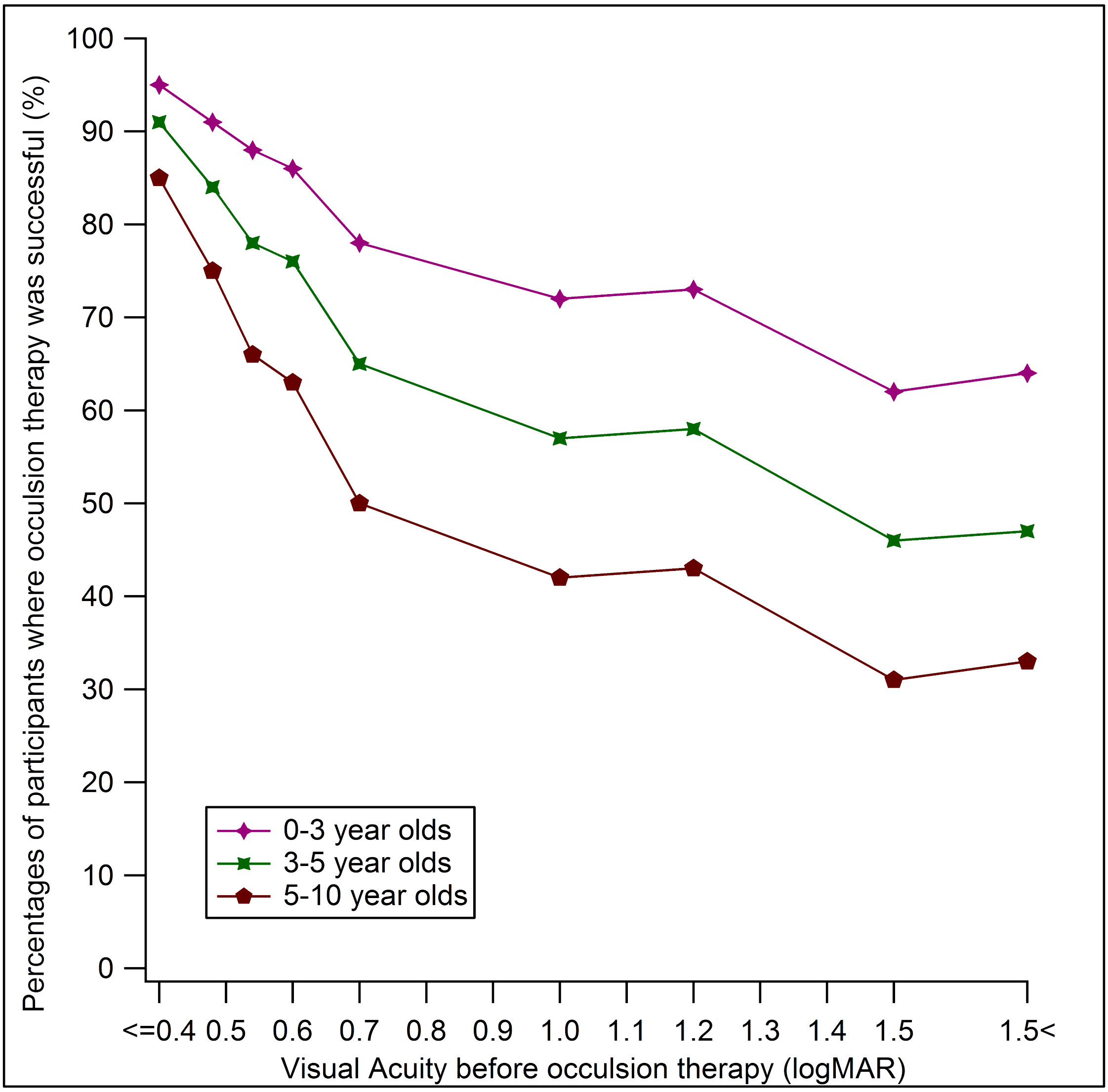


Figure 1.1: *The percentage of participants where occlusion therapy was successful (where success was defined as the visual acuity of the amblyopic eye being 6/12 or better) according to the age at which treatment was initiated and the visual acuity before treatment was initiated. Data taken from Flynn et al. (1999). Error bars not shown due to the necessary information being unavailable.*

1.4 Diagnosing amblyopia

In order for treatment of amblyopia to be initiated early in life, it is important that it is diagnosed as early as possible. Functional amblyopia is a diagnosis made by exclusion, with inter-ocular visual acuity differences (see Table 1.1) being the key component for diagnosing, monitoring and treating amblyopia (Campos, 1995; Logan and Gilmartin, 2004; Holmes and Clarke, 2006; Steele et al., 2006; Pediatric Eye Disease Investigator Group, 2006; Wallace and Tjan, 2011; O'Donoghue et al., 2012; Cotter et al., 2012; Ying et al., 2012). Currently, visual acuity charts are an important tool in diagnosing amblyopia and visual acuity charts with crowding features are considered particularly beneficial for diagnosing amblyopia (Giaschi et al., 1993; Hess et al., 2001; Hariharan et al., 2005; Levi et al., 2007; Greenwood et al., 2012).

Table 1.1: *Definitions of amblyopia used by a variety of different research papers.*

Group	Definition of amblyopia	Paper
All	>1 line inter-ocular acuity difference	(Steele et al., 2006)
Mild Moderate Severe	$2 \leq$ and <4 line difference $4 \leq$ and <6 line difference >6 line difference	(Leon et al., 2008)
All	≤ 0.2 logMAR difference	(Ying et al., 2012)
All	$\leq$ 0.3 logMAR inter-ocular difference, V/A of 0.3 logMAR or worse in the amblyopic eye and 0.3 logMAR or better in the fellow eye	(Cotter et al., 2012)
Moderate	6/12 or worse in the amblyopic eye	(Wallace et al., 2011)

Many pre-literate visual acuity charts display optotypes individually, or as individual lines of optotypes to reduce the complexity of the task. For a young child the the presence of too many letters or symbols can make the task too complex (Faye, 1968). Format and design of pre-literate visual acuity charts is discussed in Section 1.6. Visual acuity scores are lower when obtained using single optotypes compared to those obtained with single lines of optotypes, which are in turn lower (better) than scores obtained with lines of optotypes (Friendly, 1978; Morad et al., 1999; Drover et al., 2008; Langaas, 2011), discussed further in Section 3.1. Additionally, crowding features (such as a surrounding box or flanking bars) are widely considered important for detecting and diagnosing amblyopia in children (Stuart and Burian, 1962; Flom, Weymouth and Kahneman, 1963; Friendly, 1978; Giaschi et al., 1993; Hess et al., 2000; Hariharan et al., 2005). To produce a crowding effect without making the task too complex, pre-literate visual acuity charts often have a box or bars surrounding the optotype or line of optotypes.

1.5 Contour interaction and crowding

Contour interaction is a phenomenon in which resolution acuity is degraded by the arrangement of contours around the target optotype (Flom, Weymouth and Kahneman, 1963). Crowding is a phenomenon similar to, and inclusive of, contour interaction, as it includes the effect of surrounding or flanking optotypes, in addition to nearby contours (for reviews, see Levi, 2008; Whitney and Levi, 2011). Crowding is thought to include additional factors such as eye movements and attention (Danilova and Bondarko, 2007; Hairol et al., 2013; Bedell et al., 2013). The effect of crowding appears to be greater with increased flanker complexity and greater target-flanker similarity (Bernard and Chung, 2011).

It has been argued that the magnitude of contour interaction scales with acuity in normal and amblyopic eyes (Flom, Weymouth and Kahneman, 1963). However it has also been suggested that the crowding phenomenon is exaggerated in amblyopia (Stuart and Burian, 1962), particularly in strabismic amblyopia (Hess et al., 2001; Greenwood et al., 2012; Formankiewicz and Waugh, 2013; Levi et al., 2015), possibly due to the presence of unsteady fixation (Stuart and Burian, 1962). Therefore incorporation of crowding features onto a visual acuity chart may aid a clinician in diagnosing and monitoring the treatment of amblyopia.

Research investigating the effects of contour interaction and crowding have sometimes used Landolt Cs (Flom, Weymouth and Kahneman, 1963; Bach, 1996; Bondarko and Semenov, 2005; Danilova and Bondarko, 2007) or Sloan Es. Crowding features on commercially available visual acuity charts are generally placed 0.5 optotype-widths away from the target optotype or line of optotypes (Atkinson et al., 1988; McGraw and Winn, 1993; Holmes et al., 2001; Jones et al., 2003; Vision in Preschoolers (VIP) Study Group, 2005). Recently, it has been found that the crowding effect is larger when crowding features are placed closer than is currently done on commercial visual acuity charts (Formankiewicz and Waugh, 2013; Song et al., 2014). However, some researchers suggest that similarity between the target and flankers is not needed for crowding (Manassi et al., 2016) but increased target-flanker similarity makes visual search tasks harder for children due to poor oculomotor fixation stability (Huurneman and Boonstra, 2015) which improves with age (Kowler and Martins, 1982; Aring et al., 2007).

1.5.1 Use of contrast modulated stimuli

Recent research has investigated visual sensitivity to stimuli other than those defined by luminance, such as contrast-defined stimuli, and have found additional sensitivity losses in amblyopia to these stimuli, than traditional luminance stimuli (Wong et al., 2001, 2005; Chung et al., 2008*a*,*b*; Hairol et al., 2013). Therefore measurements of visual acuity using contrast-modulated noise letters may have the potential to be superior for earlier detection of amblyopia. Additional reasons for why these letters might be more effective than standard luminance ones for the detection of amblyopia are that (1) the magnitude of crowding is larger for contrast-modulated noise than luminance-modulated noise letters (Chung et al., 2008*a*; Hairol et al., 2013), and amblyopes are thought to show exaggerated crowding relative to healthy individuals; and (2) it has been suggested that contrast-modulated noise stimuli are processed in more binocular neural areas, than luminance-modulated ones (Wong et al., 2005; Waugh et al., 2009) and amblyopes have clear deficits in binocularity. The focus of this research project will be to determine whether contrast-modulated noise letters/symbols designed for children could provide a more effective tool for the earlier detection of amblyopia.

In order to determine whether crowding with contrast-modulated (CM) optotypes is exaggerated in amblyopia and to quantify the degree to which crowding is exaggerated in amblyopia with isolated child-friendly optotypes, it is important to first describe what is known about the effects of crowding in normal vision with standard luminance stimuli.

1.5.2 Contour interaction and crowding in normal adults and children

One of the first studies was done by Flom, Weymouth and Kahneman (1963) and they found the largest detrimental effect of surrounding contours was when the distance between the target optotype and the surrounding contours was twice the size of the gap in the Landolt C optotype (two stroke widths or 0.4 letter widths).

Jeon et al. (2010) investigated how far out three parallel bars on all four sides of a Sloan E could be moved before no crowding or contour interaction was seen with adults and children. For adults this was 2.83 times the width of the lines, and 7.30, 7.84 and 7.13 times the line width for children aged 5, 8 and 11 years old, respectively. The distance over which crowding occurred was significantly larger ($p<0.005$) with children than adults. Atkinson et al. (1988) compared visual acuity with isolated letters (H, O, T, V and X) with that obtained with the same letters surrounded by other letters (A, C, L and U) placed 2.5 stroke widths (half a letter width) away. The detrimental effect of the surrounding letters was larger with 3 to 4 year olds (ratio of 1.8) than 5 to 7 year olds and adults (ratio of 1.2). Shah et al. (2010) investigated crowding using their own letter chart (compLOG) which showed single lines of letters surrounded by a box. They observed crowding when the separation was 1.25 and 1.9 stroke widths but not when the separation was 2.5 stroke widths (half a letter width) as is commonly used on "crowded" children's letter charts. The separation is half a letter width on the Keeler LogMAR chart (previously known as the Glasgow Acuity Cards) (McGraw et al., 2000) based on the findings of Flom, Weymouth and Kahneman (1963) . Norgett and Siderov (2011) measured visual acuities of 103 children aged 4 to 6 and 7 to 9 years using five commercially available visual acuity charts: one uncrowded and two crowded letter charts and one uncrowded and one crowded symbol chart. The letter charts were the Sheridan-Gardiner test (uncrowded), LogMAR Crowded test (half an optotype width or 2.5 stroke widths separation) and the Sonsken chart (one optotype width or 5 stroke widths separation). The picture charts were the Single (uncrowded) and Crowded (5 stroke widths or half an optotype width separation) Kay Picture test. Crowding was larger with the younger age group (4 to 6 years old) than the older age group (7 to 9 years old).

In this study, the magnitude of crowding is investigated with individually displayed standard luminance (L), luminance-modulated (LM) and contrast-modulated (CM) optotypes with a wide range of target-flanker separations in normal adults. Then with children, acuity is measured with the optimal flanker placement, and without flankers only (to reduce the length of the task). Very little is currently known about the magnitude of crowding in children of different ages. This study will look at the magnitude of crowding, with L, LM and CM optotypes and with flanking letters as well as a surrounding box, for children aged 3 to 16 years.

1.5.3 Crowding in amblyopic vision

Elliott and Firth (2009) compared uncrowded and crowded versions of the Kay Picture chart and Keeler LogMAR chart with 51 amblyopes aged between 5 years 1 month and 45 years 10 months, with a mean age of 10 years 8 months. Of the 51 amblyopes, 17 had strabismus, 10 had anisometropia and 24 had strabismus and anisometropia. All the amblyopes were categorised based on the visual acuity of their amblyopic eye as mild (better than 0.25 logMAR) or moderate/severe (worse than or equal to 0.25 logMAR). The detrimental effect of crowding was investigated by comparing the thresholds measured using the crowded chart to those measured using the uncrowded chart. The effect was larger (0.153 logMAR and 0.130 logMAR) for the moderate/severe amblyopes than the mild amblyopes (0.125 logMAR and 0.075 logMAR) for the Keeler LogMAR and Kay Picture charts respectively. Hess et al. (2001) investigated the extent of contour interaction with eight strabismic amblyopes using a gap detection orientation task with a Landolt C. The crowding extended out as far as ten stroke widths for three of the eight amblyopes, but was within the normal range found in normal observers for a further three amblyopes. Thus, the effect of crowding in amblyopia remains unclear and it is likely that the relationship between amblyopia and crowding is complex, leading to some amblyopes suffering from an exaggerated effect of crowding whilst the effect of crowding in other amblyopes is comparable to normals. They concluded that "there is no doubt that contour interaction is abnormal in amblyopia even when their acuity loss is taken into account" (Hess et al., 2001).

When amblyopia was mimicked using different levels of blur (for anisometropic amblyopia) and different degrees of eccentric fixation (for strabismic amblyopia), systematic investigation of target and flanker separation in paediatric visual acuity charts showed that the magnitude of crowding is greater with a 0.25 optotype width gap (equal to 1.25-2.50 stroke width gap) between the target optotype and flankers (Formankiewicz and Waugh, 2013). Size and spacing requirements of crowding using letters were investigated using blur and eccentric fixation in normal adults, as well as six strabismic, six anisometropic and six mixed amblyopes. With the mimicked and real pure anisometropic amblyopia, the acuity was affected but not the critical spacing. With mimicked and real strabismic amblyopia, the critical spacing was affected but not the visual acuity (Song et al., 2014). Both studies found that there was unlikely to be much if any crowding on current commercially available charts and recommended that the target-flanker separation be reduced (Formankiewicz and Waugh, 2013; Song et al., 2014).

In this study, the magnitude of crowding with optimally placed crowding features (determined in this study) with L, LM and CM child-friendly target optotypes is investigated and compared against the magnitude of crowding observed with normal adults and normal children aged 3 to 16 years. This will enable comparison of the magnitude of crowding with L, LM and CM stimuli for amblyopic adults compared to normal adults as well as drawing comparisons with the normal developmental time-course.

1.6 Pre-literate visual acuity charts

Amblyopia is a common developmental disorder of spatial vision (Flom and Neumaier, 1966; Attebo et al., 1998; Flynn et al., 1998, 1999; Robaei et al., 2006; Williams et al., 2008; Elflein et al., 2015) thought to be due to the disruption of the normal development of binocular vision in early life (Wiesel and Hubel, 1963; Rauschecker and Singer, 1981; Crawford et al., 1983; Horton and Stryker, 1993; Wensveen et al., 2001; Zhang et al., 2003; Conner et al., 2007; Joly and Frankó, 2014) characterised by reduced visual acuity in an otherwise healthy eye (Cole, 1959; Flom and Neumaier, 1966; Attebo et al., 1998; Eibschitz-Tsimhoni et al., 2000; Chua and Mitchell, 2004; Simons, 2005; de Koning et al., 2013).

Amblyopia is diagnosed based on poor visual acuity (Cole, 1959; Yassur et al., 1972; Hopkisson et al., 1982; Jensen and Goldschmidt, 1986) and/or an inter-ocular difference in visual acuity (Hopkisson et al., 1982; Vaughan et al., 1960; Vinding et al., 1991). Visual acuity charts are an important tool for measuring spatial acuity and consequently for diagnosing amblyopia (Davidson and Eskridge, 1977; von Noorden, 1985; Simmers et al., 1997). Visual acuity charts used with adults normally consist of lines of letters, for example the Snellen and Bailey-Lovie (Bailey and Lovie, 1980)) charts. It is widely accepted that such charts are unsuitable for use with young, particularly pre-literate, children (Sheridan, 1960; Ffooks, 1965; Sheridan and Gardiner, 1970; Keith et al., 1972; Kay, 1983; Hodes et al., 1994). As noted in Section 1.3, the younger the age at which a visual defect is diagnosed, the more favourable the outcome (Sheridan, 1960; Sheridan and Gardiner, 1970; Friendly, 1978; Flynn et al., 1998, 1999). As a result, many charts have been designed with the intention of creating a visual acuity chart that is more suitable for use with young children.

A variety of approaches are taken with the design of different pre-literate visual acuity charts. Some are aimed at children who are learning their letters, or who can read but not reliably (approximately 5 to 7 years old), these are discussed in Section 1.6.4. For younger children, pictures or symbols can be used instead of letters. Examples of such charts are: Modified Pictograph Method (Fink, 1945), Allen Cards (Allen, 1957), American Optical Kindergarten Vision Test (Rychener, 1958), Ffooks (Ffooks, 1965), Bealle Collins (Keith et al., 1972), Lea Symbols (Hyvärinen, 1982), Kay Pictures (Kay, 1983) and Wright Figures (Hrisos et al., 2004). Details of these charts can be found in Table 1.2.

Table 1.2: *Picture and symbol visual acuity tests.*

Test	**Paper**	**Optotypes**
Allen cards	(Allen, 1957)	Telephone, car, horse and teddy bear.
American Optical	(Rychener, 1958)	Boat, circle, cross, simple flag, star, heart, hand, cup and quarter moon.
Ffooks	(Ffooks, 1965)	Circle, square and triangle.
Bealle Collins	(Keith et al., 1972)	Boat, bicycle, chair, house, flower, cup, rocking horse, rabbit, chicken, ladder, table, elephant, key, duck, gate and scissors.
Lea Symbols	(Hyvärinen et al., 1980)	Apple/heart, circle, house and square
Kay Pictures	(Kay, 1983)	Apple, boot, clock, cup, duck, fish, house and truck.
Wright figures	(Hrisos et al., 2004)	Cup, house, cow, train and duck.

Some pre-literate visual acuity charts, instead of having an optotype that needs to be identified, require identification of orientation, for example: Landolt C, Rotated E, Incomplete Square, Marquez-Bostrom Square and Broken Wheel Test. These are discussed in Section 1.6.2.

There are a huge number of pre-literate visual acuity charts. In this review, the main charts considered to be of relevance to the proposed project will be described. Section 1.6.1 discusses visual acuity charts that use gratings, which are used with babies and very young children but do not normally produce sufficient interest from two years of age. They are mentioned here only to give an overview of how visual acuity is tested prior to the age range of interest in this study (3 to 16 years of age).

1.6.1 Grating charts

Grating charts (e.g. Teller Acuity Cards) are the simplest with respect to the task required of the person being tested (Teller, 1979). They comprise of a card with both a grating pattern and a homogenous grey area. They were designed to enable testing of visual acuity and contrast sensitivity of babies and very young children (McDonald et al., 1985). The principle used is that when a baby or very young child is shown a card with a grating and a homogenous grey card simultaneously, they will look towards the side with the grating on it because it is "more interesting" to them (Frantz et al., 1962). Monocular acuity norms have been produced for children aged between 1 month old and 4 years old (Mayer et al., 1995). The Teller Acuity Cards show good inter-observer test-retest reliability to within an octave (within studies and age groups, the normal acuity range is 2-4 octaves) (Birch and Hale, 1988; Salomão and Ventura, 1995; Mayer et al., 1995; Getz et al., 1996; Harvey et al., 1999). Drover et al. (2009) assessed monocular grating acuity and optotype acuity in 45 patients with amblyopia, 44 patients considered at risk of amblyopia and 37 children with no known vision problems. Visual acuities were categorised as normal and abnormal with gratings and optotypes. The categories were in agreement for 76% of the 126 participants, with better agreement in the case of moderate (79%) and severe (83%) amblyopia. This indicates that, in the case of babies and toddlers that are unable to co-operate with testing with an optotype based visual acuity test, a grating acuity test such as the Teller Acuity Cards is a reasonable alternative. However, grating charts do not produce sufficient interest to engage the majority of toddlers and older children. The Cardiff Acuity Test (also known as the Vanishing Optotypes Test) is a special kind of grating chart produced by Woodhouse et al. (1992). It consists of pictures where the lines are made up of gratings with the remainder a homogenous grey so that the picture can only be seen if the gratings can be resolved. In most cases where grating charts do not produce sufficient interest, the person will be able to engage with a chart with letter, picture or symbols optotypes and the Cardiff Acuity Test has been found to be useful with children and adults with intellectual disability (McCulloch et al., 1996; Woodhouse, 1998; van den Broek et al., 2006; Woodhouse et al., 2007; Johnson et al., 2009). Grating acuity tests, including the Cardiff Acuity Test, are conducted by showing a card (one side of which contains the grating, the other contains a homogenous grey field) using a two alternative forced-choice procedure to determine visual acuity estimates.

1.6.2 Rotated letter tests

Another group of pre-literate visual acuity tests have a letter that is rotated and the orientation of the letter is indicated. These tests are most commonly based on either the Landolt C (for example: Landolt C, Marquez-Bostrom Square and Broken Wheel Test) or the Tumbling E (for example: Tumbling E, Michigan Junior Vision Screener and B-S Hand). The primary advantage of the orientation tasks is that the child does not need to be able to identify optotypes. However, it has been observed that young children have difficulty with orientation tasks (Rice, 1930; Davidson, 1934, 1935; Newhall, 1937; Wohlwill, 1960). Consequently, there is a high chance of a child giving an incorrect response even if the optotype is seen correctly. Confusion about the horizontal axis (up-down confusion) is common until 5 years of age (Davidson, 1935). Confusion about the vertical axis (left-right confusion) is more common than up-down confusion (Davidson, 1934; Sekuler and Rosenblith, 1964) and is commonly problematic up to 7 years of age, which can be an issue even when the required response involves pointing in the correct direction (Hanfmann, 1933; Newhall, 1937; Wechsler and Pignatelli, 1937; Sheridan, 1960; Teuber, 1963; Cairns and Steward, 1970; Lippmann, 1971; Friendly, 1978; Simons, 1983).

1.6.3 Picture and symbol charts

Picture and symbol charts use simple pictures or symbols instead of letters. Different design approaches exist for both the choice of pictures/symbols and the chart design. These charts are normally designed with young children in mind because they are the target age group. The most widely used are considered here.

Kay Pictures test

The Kay Picture chart is a popular pre-literate visual acuity test in the U.K. and was designed by Kay (1983) using the same design principles as the Snellen letters but to maintain interest for 2 to 3 year olds. The Snellen letters were designed on a 5×5 grid, such that one stroke width (which is equal to the width or height of each "box" on the grid) on the 6/6 letters subtends 1 arcmin at 6 metres. The Kay Pictures were designed on a 10×10 grid such that the stroke width (or grid width/height) on the 6/6 pictures subtends 1 arcmin at 6 metres (Kay, 1983; O'Connor et al., 2010). The larger grid size was used to allow for enough detail to design pictures that young children would be able to recognise and that would hold their interest. This is demonstrated in Figure 1.2.

Vision was measured for 160 adults and older children, using both the original 38 Kay Pictures optotypes and the Snellen. A strong correlation was found between the measurements taken with the Kay Pictures symbols and Snellen chart (r=0.90) with approximately 50% of participants obtaining the same measurement on the two charts and vision was measured to be the same (or not more than 1 line less). Eight of the optotypes were included in a screening version of the Kay Picture chart. It was decided that 8 would be a small enough number for children to be able to match the optotypes on a matching card but large enough to keep the guess rate low and maintain interest throughout testing (Kay, 1984). A variety of Kay Picture visual acuity charts are currently available commercially. There are crowded and uncrowded versions and 3 of these are designed for testing near vision, one for distance vision and four for testing both distance and near vision. Of these eight charts, all but one (the Near Vision Test Card) contain only the reduced set of eight picture optotypes.

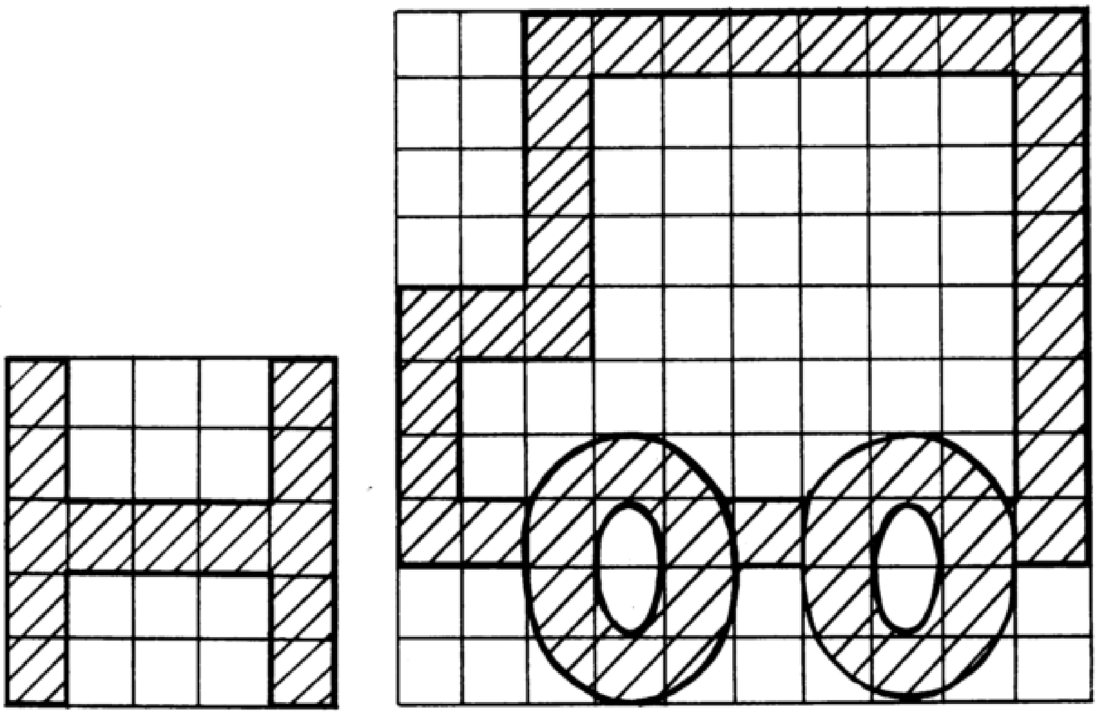


Figure 1.2: *A Snellen "H" on a* 5×5 *grid compared to a Kay Picture "Truck" on a* 10×10 *grid. The Snellen letters were designed on a* 5×5 *grid as shown, whereas the Kay Picture optotypes were designed on a* 10×10 *grid as shown to allow more detail. Picture taken from Kay (1983).*

Lea Symbols

The Lea Symbols chart is one of the most popular pre-literate visual acuity charts in Europe, Australia and the USA. The Lea Symbols chart was originally called the LH symbols chart, and in some places it still is. It was designed by Hyvärinen et al. (1980) with the intention of creating a visual acuity chart suitable for use with young children. The chart consists of four different symbols: an apple/heart, a circle, a house and a square (see Figure 3.7, Section 3.3.3). The symbols were intended to be easily recognisable by young children. Basic symbols were used to avoid cultural bias affecting visual acuity scores. To make the symbols effective for visual acuity testing they were designed to be equally legible but difficult to discriminate at the limits of acuity. The dip on the apple/heart was drawn such that the apple/heart would be difficult to distinguish from the circle at the limits of acuity. The "roof" on the house was drawn in such a way that the house and square would be difficult to distinguish at the limits of acuity. Such difficulty in distinguishing optotypes at the limits of acuity is important but it is not true of all pre-literate visual acuity tests. For example, the Allen Cards optotypes have a very distinct shape even when blurred (Mocan et al., 2005).

In a study by Hyvärinen et al. (1980) visual acuity obtained using the Lea Symbols chart were compared against those obtained using the Snellen E test, which also consisted of multiple rows of optotypes. The Snellen E test was chosen because it was the international reference optotype at the time (Visual Functions Committee, 1988). A high percentage of 3 year olds ($\geq 75\%$) and 4 to 5 year olds ($\geq 97\%$) could be tested using the Lea Symbols test. Figure 1.3 shows the percentage testable for the Lea Symbols test for single optotypes and multiple lines of symbols with 3 to 5 year olds. The percentage testable increases with age. The differences in testability within age groups between studies could be explained in part by the testers having different levels of experience (Hered and Rothstein, 2003; Schmidt et al., 2004).

1.6.4 Pre-literate letter charts

Such charts use a limited selection of letters (see Table 1.3), normally only those that are vertically symmetrical because these letters are widely considered the easiest to read (Davidson, 1935; Wechsler and Pignatelli, 1937; Graham and Berman, 1960; Cairns and Steward, 1970) due to orientation confusion, especially about the vertical axis, which is common in young children (Rice, 1930; Davidson, 1934; Newhall, 1937; Wohlwill, 1960). Additionally, vertically symmetrical letters allow for the charts to be used with or without a mirror, which gives the clinician more flexibility. Keeping to a limited selection of letters also provides the option of a matching card (too many letters on a matching card would make it too complex for a young child to use). Examples of charts that use this approach are: STYCAR (Sheridan, 1960), HOTV (Lippmann, 1971) and Cambridge Crowding Cards (Atkinson et al., 1986).

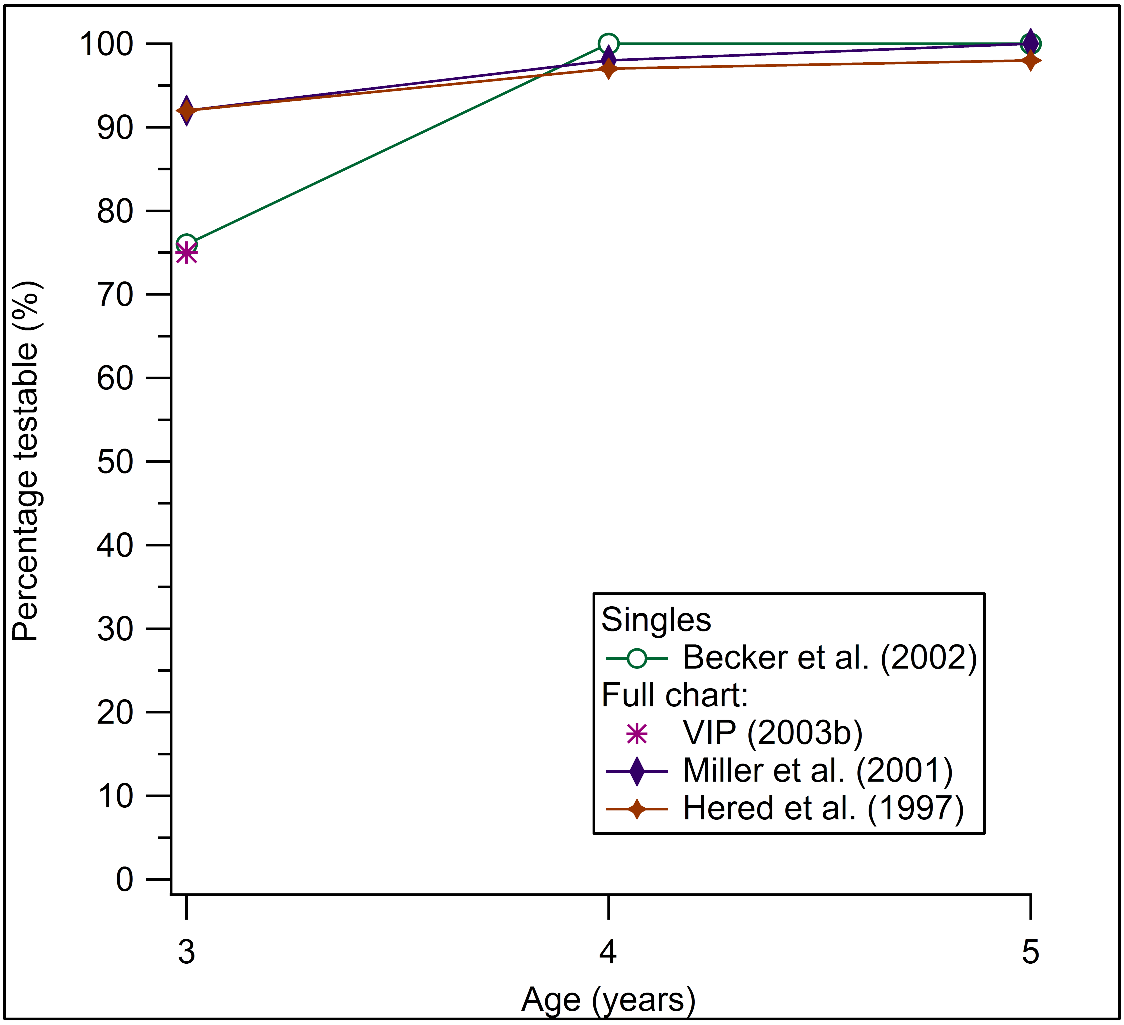


Figure 1.3: *The percentage of children aged 3-5 years old that could be tested using the Lea Symbols chart according to a variety of studies (Hered et al., 1997; Miller et al., 2001; Becker et al., 2002; Vision in Preschoolers (VIP) Study Group, 2003*b*). Error bars not shown due to the necessary information being unavailable.*

Table 1.3: *The optotypes used in a variety of pre-literate visual acuity tests. Optotypes in brackets are not target optotypes.*

Visual acuity test	Optotypes
STYCAR	H O T V X A U C L
Sheridan-Garinder	H O T V X A U
HOTV	H O T V
Cambridge Crowding Cards	H O T V X (A U C L)
Keeler logMAR	H O V X U Y

STYCAR

The STYCAR (Sight Test for Young Children And Retards) chart was developed by Sheridan (1960) due to an observation that some children, particularly children with intellectual disabilities, found it difficult to relate black on white stylised pictures to the objects that they were supposed to represent. Extensive testing with direction based tests (such as the E test and the Sjögren Hand test) showed that in less favourable conditions (such as schools) they were more difficult to use than in more favourable conditions (such as in research and clinical settings). The limited number of options and the frequent confusion between left and right in young children also meant that such tests are not ideal. Sheridan (1960) chose nine letters (H, O, T, V, X, A, U, C and L) based on the shapes that she observed five year old children could copy. These letters were shown individually. Sheridan (1960) observed that children aged between 3 and 5 years of age could match but not copy letters which lead to the development of matching cards. They responded more satisfactorily to single letter cards, than to the whole chart. The examiner found it difficult to maintain a rapport with younger children at a distance of 6m, which was solved by sitting beside the child while using a mirror. Consequently, Sheridan (1960) recommended that a reduced set of seven letters be used with younger children where a mirror was needed. A reduced set of 5 letters (H, O, T, V and X) was recommended by Sheridan with children (primarily 2 to 3 year olds) who found the letters U and A too difficult to discriminate (although most 4 year olds could). Sheridan (1960) noted that some 2 year olds often confused the V and X and recommended that for these children the

X be covered to enable testing of such children, noting that this still gives a choice of four differently shaped letters (H, O, T and V).

Sheridan-Gardiner

The seven letter version of the STYCAR test mentioned above was later developed into a portable vision screening test by Sheridan and Gardiner (1970) with the intention that it be usable in school conditions for assessing near and distance vision.

The aim was to produce a chart that could be used for children aged between 5 and 7 years of age, especially those with other handicaps, particularly mental handicaps, due to a higher incidence of vision problems with these children (Gardiner, 1967) and earlier diagnosis leading to a more favourable outlook for improvement in function (Sheridan and Gardiner, 1970). Several formats were developed, including single letter acuity cards for 6m and 3m, a near visual acuity test with multiple letters (at least six letters of each size from 6/60 to 6/6, reduced Snellen and reduced Roman N18 to N5) and a distance illuminated panel chart (with letters from 6/60 to 6/6 included), with the option of hooking single letters onto it. The Sheridan-Gardiner chart single letter format has been criticised because of their potential reduced usefulness for detection of amblyopia (Hilton and Stanley, 1971; Langaas, 2011). Sheridan defended single letter presentation and the wide spacing between letters on the panel chart, saying that children under 7 years of age are impelled to concentrate on each letter individually and therefore should be unaffected by crowding (Sheridan and Gardiner, 1970).

HOTV test

The HOTV test contains the four letters suggested by Sheridan (1960) to be best for measuring visual acuity in 2 to 3 year olds. Lippmann (1971) coined the term “HOTV” test and was the first person to use the four letters as a test in its own right rather than a reduced version of the STYCAR or Sheridan-Gardiner test for children unable to do the full set of seven or nine letters, as recommended by Sheridan (1960). The letters used in the HOTV test are all vertically symmetrical to allow the use of a mirror, and therefore for the tester to be next to the child rather than 6m away, for easier testing of young children without changing the test distance (Sheridan, 1960). As previously mentioned, young children have difficulties with left and right that extends to greater difficulties with reading, matching and identifying non-vertically symmetrical letters (Newhall, 1937; Wohlwill, 1960; Cairns and Steward, 1970).

The Vision in Preschoolers (VIP) Study Group (2003*a*) were able to test a high proportion (71%) of 87 children aged between 3 and 3.5 years of age using a computer-based crowded HOTV distance acuity chart. The test used displayed individual letters surrounded by flanking bars on a computer monitor. The distance between the letters and the flanking bars is not stated but in the picture of the chart, the gap is approximately half an optotype in size.

Cambridge Crowding Cards

The Cambridge Crowding Cards uses the five letters recommended by Sheridan (1960) and used in the STYCAR chart (H, O, T, V and X) with the remaining four letters (A, U, C and L) placed in a random order above, below, left and right, half an optotype distance away as crowding features. Letters constitute larger crowding features than flanking bars or a surrounding box. However, it has been suggested that larger crowding features result in a paradoxical decrease in the magnitude of crowding (Levi and Li, 2009*a*; Manassi et al., 2013). The 0.5 optotype width target-flanker separation is based on the results of Flom, Weymouth and Kahneman (1963) showing the optimal crowding at 0.4 optotypes away rounded up to 0.5 optotypes width (Atkinson et al., 1988). Two versions of the Cambridge Crowding Cards were originally developed: one for use at 3m and the other for use at 6m. Co-operation was better at 3m than at 6m and so only the 3m version was retained (Atkinson et al., 1988).

Keeler LogMAR crowded test (formerly Glasgow Acuity Cards)

The LogMAR Crowded Test, originally called the Glasgow Acuity Cards (Jones et al., 2003), were designed by McGraw and Winn (1993) to improve visual acuity testing of 3 to 5 year olds. The cards have a line of four letters with a surrounding box, which is included for the purpose of improving detection of amblyopia. The letters used are: H, O, V, X, U and Y, which were selected because they were equally legible and vertically symmetrical. Each card has four letters of the same size; the consistent number of letters on each card is to make the task equally difficult for each letter size. Increasing the number of letters per line as letter size reduces changes the difficulty of the task across the chart which could influence visual acuity measurement. The stroke width of the surrounding box (line width) is equal to the stroke width of the letters. The inter-letter separation is 0.5 optotype widths, which is identical to the letter-box separation.

1.7 Comparisons of measures of visual acuity using different acuity tests

Measurements of visual acuity differ between tests (see Figure 1.4). In this section, visual acuity measurements with letter based tests are compared to acuities measured with Kay Pictures and Lea Symbols tests.

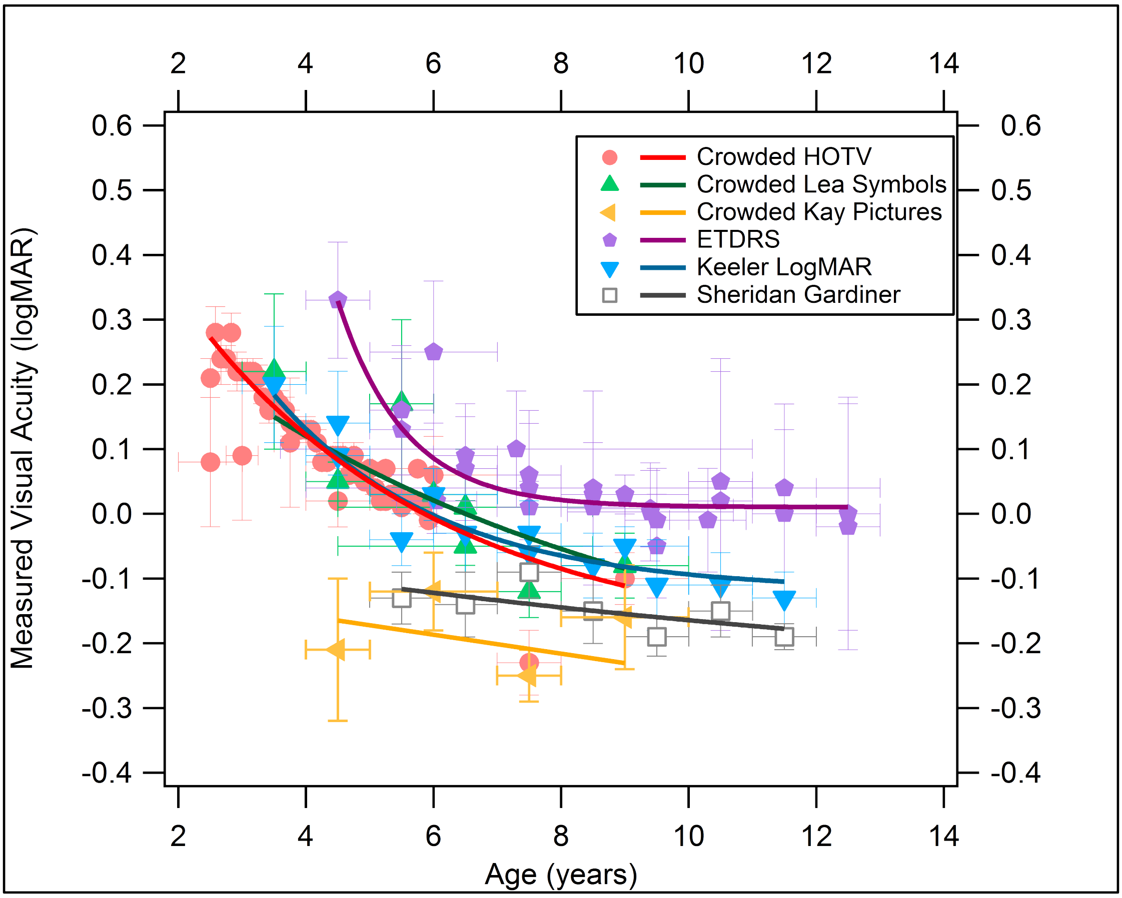


Figure 1.4: *Visual Acuity measurements from different published papers (Myers et al., 1999; Hazel, 2002; Manny, 2003; Chen et al., 2006; Shea and Gaccon, 2006; Pan, Tarczy-Hornoch, Cotter Susan, Wen, Borchert, Azen and Varma, 2009; Dobson et al., 2009; O'Donoghue et al., 2010; Langaas, 2011; Sanker et al., 2013; Leone et al., 2014; Anstice et al., 2017*a*), measured using children with normal vision. Data points indicate the mean Visual Acuity for each participant group from each paper with lines of best fit through all points contributing to each test. The x error bars indicate the age range of participants contributing to that data point. The y error bars indicate* ±1*SD.*

Visual acuity measured with the Kay Pictures test compared to letter based tests

The Kay Pictures test has been shown to overestimate visual acuity by 1 to 2 lines in non-amblyopic adults and children when compared to visual acuity measured with ETDRS, Keeler logMAR and HOTV letter based visual acuity tests (Norgett and Siderov, 2011; Shah et al., 2012; Anstice et al., 2017*b*), but not when compared to the Sonsken or Sheridan Gardiner tests. The amount that the Kay Pictures test has been shown to overestimate visual acuity in amblyopes ranges from less than 1 line (for example: Elliott and Firth, 2009) to more than 2 lines (for example: Shah et al., 2012) when compared to visual acuities measured using the Keeler logMAR or ETDRS letter based visual acuity tests.

Anstice et al. (2017*b*) measured visual acuity using popular pre-literate visual acuity tests (ETDRS, HOTV, Kay Pictures, Lea Symbols and Keeler logMAR tests) with 25 adults and 17 children (4 to 9 years old) and demonstrated that measurements using the Kay Pictures test overestimate visual acuity by 1 to 2 lines in adults (0.16 ± 0.02 logMAR) and children (0.20 ± 0.04 logMAR) compared to measurements made with the letter based tests (Anstice et al., 2017*a*). Visual acuity measured with the Kay Pictures test was also 1 to 2 lines better than with the Lea Symbols test in adults (0.17 ± 0.03 logMAR) and children (0.15 ± 0.04 logMAR). In the presence of +1.00DS optical blur, the 1 to 2 line difference in visual acuity measurements between Kay Pictures and letter based tests remains in both adults (0.14 ± 0.03 logMAR) and children (0.15 ± 0.08 logMAR).

Elliott and Firth (2009) measured the visual acuity of 52 amblyopic participants using the crowded Kay Picture test and the crowded Keeler LogMAR test. Participants were aged between 5 years 1 month and 45 years 10 months (mean age 10 years 8 months). Visual acuities measured with the moderate/severe amblyopes (visual acuity ≥ 0.25 logMAR in the amblyopic eye) were significantly lower (p=0.038) with the Kay Picture test than the Keeler LogMAR test (0.07 ± 0.04 logMAR lower) but were not significantly different (p=0.94) with the mild amblyopes (visual acuity <0.25 logMAR in the amblyopic eye) between the Kay Picture and Keeler logMAR tests (0.00 ± 0.03 logMAR difference). Visual acuity measured for non-amblyopic adults with various ophthalmic diseases were 0.10 ± 0.03 logMAR better when measured with the crowded Kay Pictures test than when measured with the ETDRS test. With amblyopic children the visual acuity measurements with the Kay Pictures test were 0.21 ± 0.01 logMAR better than when measured with the ETDRS test.

Norgett and Siderov (2011) measured visual acuity in 103 children aged 4-9 years old. The crowded Kay Picture test (0.5 optotype width spacing) overestimated visual acuity compared to the Keeler logMAR test (0.5 optotype width spacing) by 0.10 ± 0.02 logMAR with the younger age group (4 to 6 years old) and the older age group (7 to 9 years old). The Sonsken test has a 1.0 optotype width spacing and produced visual acuity estimates that were higher than with the crowded Kay Picture test (0.03 ± 0.02 logMAR and 0.06 ± 0.02 logMAR with the younger and older age groups respectively) and the uncrowded Kay

Picture test (0.08 ± 0.02 logMAR and 0.07 ± 0.02 logMAR with the younger and older groups respectively). The Sheridan Gardiner test which contains individual isolated optotypes resulted in similar visual acuity estimates to the uncrowded Kay Picture test with both the younger (0.03 ± 0.02 logMAR difference) and older (0.01 ± 0.02 logMAR difference) age groups.

Visual acuity measured with the Lea Symbols test compared to letter based tests

Visual acuity measurements in normal adults are similar when obtained using the Lea Symbols to those obtained using letter based tests (Candy et al., 2011; Anstice et al., 2017*b*). With children, visual acuity measurements with Lea Symbols are similar to those obtained using letter based tests (Anstice et al., 2017*b*) and rotated letter tests (Sanker et al., 2013) except when the Lea Symbols test is presented as a full chart or when the letters are presented individually (Vision in Preschoolers (VIP) Study Group, 2003*a*; Omar et al., 2012).

Visual acuity measured with 25 non-amblyopic adults were similar with the Lea Symbols test and letter based acuity tests (ETDRS, HOTV and Keeler logMAR tests) with an overall difference of 0.01 ± 0.02 logMAR. With 17 amblyopic children (4 to 9 years old) visual acuity estimates were similar between the Lea Symbols test and pre-literate letter based tests (0.00 ± 0.03 logMAR difference) but visual acuity estimates with the ETDRS test were 0.12 ± 0.05 logMAR worse than with the Lea Symbols test (Anstice et al., 2017*b*,*a*). This difference may be due to the ETDRS test being cognitively more difficult than the other visual acuity tests.

Sanker et al. (2013) measured visual acuity in 28 children aged 3 to 4 years and 19 children aged 5 to 6 years using the Lea Symbols test and the Bailey-Lovie Tumbling E. Visual acuity measurements were significantly better ($p<0.001$) when measured with the Lea Symbols test than with the Bailey-Lovie Tumbling E (0.07 ± 0.03 logMAR better) with the 3 to 4 year olds but were not significantly different ($p>0.05$) with the 5 to 6 year olds (0.03 ± 0.04 logMAR difference). Given the known difficulties in orientation discrimination in young children (Rice, 1930; Davidson, 1934, 1935; Newhall, 1937; Wechsler and Pignatelli, 1937), the acuity difference may be due to difficulty with orientation discrimination.

Vision in Preschoolers (VIP) Study Group (2003*a*) measured visual acuity in 87 children aged 3-3.5 years old using the HOTV test with letters displayed individually with flanking bars and the Lea Symbols test in a full chart format (i.e. multiple rows of optotypes displayed at the same time). Visual acuity measurements were 0.25 logMAR better with the HOTV test than the Lea Symbols test. Omar et al. (2012) also measured visual acuity using the Sheridan Gardiner test (individual HOTV letters without crowding features) and using a Lea Symbols test in a full chart format on 775 children aged 4-6 years old. Visual acuity measurements were 0.16 logMAR better with the Sheridan Gardiner test than with the Lea Symbols test. In both cases it is likely that the better visual acuity measurements with the letters is primarily due to the differences in test format rather than the optotype design.

Candy et al. (2011) measured binocular visual acuities of eight adults. Visual acuity measurements were compared against the Landolt C test, the international reference optotype at the time of publication (Visual Functions Committee, 1988) and visual acuity measurements were compared across individual optotypes, particularly within tests. Visual acuity measured with Lea Symbols and the HOTV test were both lower (better) than with the Landolt C. Visual acuities were 0.06 ± 0.04 logMAR lower when measured with the HOTV test than the Lea Symbols test and the HOTV but not the Lea Symbols test produced significantly lower (p=0.029) acuities than with the Landolt C. The discriminability of optotypes within tests was more similar between pairs of optotypes with the Lea Symbols, where there was no significant difference in pairwise similarity between pairs of optotypes (p>0.05) than the HOTV test, where optotype pairs were significantly different in discriminability (p<0.001).

1.8 Normal development of visual acuity

As discussed earlier in this review, amblyopia is currently a diagnosis made by exclusion, where reduced visual acuity is present in the absence of any pathology, even with any refractive error corrected, particularly where there is a history of strabismus and/or anisometropia (Flom and Neumaier, 1966; Hess et al., 1985; Barbeito et al., 1987). In order to determine whether visual acuity is reduced in children, it is necessary to know age norms for visual acuity. The normal development of visual acuity and the age at which visual acuity becomes adult-like has been investigated in a variety of studies using a variety of tasks and stimuli.

1.8.1 Grating acuity

As discussed in Section 1.6.1, visual acuity tests using gratings are often used with infants and pre-verbal toddlers where optotype acuity is not possible. As shown in Table 1.4 the acuity appears to become adult-like between 3 and 6 years of age (Catford and Oliver, 1973; Mayer and Dobson, 1982; Birch and Hale, 1988; Mayer et al., 1995; Lewis and Maurer, 2005).

Table 1.4: *The age at which grating acuity becomes adult-like according to a range of studies.*

Research paper	Age at which visual acuity becomes adult-like	Task
Catford and Oliver (1973)	3 years old	Maintained fixation
Birch and Hale (1988)	3 years	Preferential looking
Lewis and Maurer (2005)	4-6 years old	Preferential looking
Mayer and Dobson (1982)	5 years old	Preferential looking
Stiers et al. (2003)	>5 years old	Preferential looking
Mayer et al. (1995)	>5 years old	Preferential looking
Ellemberg et al. (1999)	6 years old	Detection

1.8.2 Optotype acuity

While grating acuity is useful, it is less sensitive to optical blurring than optotype acuity (Thorn and Schwartz, 1990) so will overestimate poorer acuities and will be less sensitive to inter-ocular differences (Woodhouse et al., 2007; Johnson et al., 2009).

Visual acuity measured with orientation discrimination tasks appears to become adult-like between 5 and 6 years of age (Simons, 1983; Lai et al., 2007). It should be noted that up/down orientation confusion is common until 5 years of age and left/right orientation confusion is common until 7 years of age (Rice, 1930; Davidson, 1934, 1935; Newhall, 1937; Wohlwill, 1960). The ages at which visual acuity is considered adult-like on orientation discrimination tasks is in line with the age at which orientation confusion becomes much less common and so it is possible that orientation confusion is influencing these results.

Table 1.5: *The age at which visual acuity becomes adult-like according to a range of studies measured with an orientation discrimination task.*

Research paper	Age at which visual acuity becomes adult-like	Stimulus	Format
Simons (1983)	6 years old	Landolt C	Crowded
Atkinson and Braddick (1982)	>5 years old	Landolt C	Crowded
Lai et al. (2007)	5 years old	Tumbling E	Linear
Lai et al. (2007)	6 years old	Landolt C	Linear
Stiers et al. (2003)	>5 years old	Landolt C	Isolated
Atkinson et al. (1986)	5 years old	Landolt C	Isolated
Atkinson et al. (1986)	>5 years old	Landolt C	Crowded

Table 1.6: *The age at which visual acuity becomes adult-like according to a range of studies measured with an optotype recognition task.*

Research paper	Age at which visual acuity becomes adult-like	Stimulus	Format
Drover et al. (2008)	6 years old	HOTV	Flanking bars
Pan et al. (2009)	$\geq$ 6 years old	HOTV	Flanking bars

In summary, there appears to be a correlation between the complexity of the task required of the child and the age at which the study concluded that visual acuity was adult-like. For example, Catford and Oliver (1973) concluded that visual acuity is adult-like by three years of age using a grating stimulus on a Nystagmus Drum. Lai et al. (2007) and Simons (1983) who asked children to identify the orientation of direction-based optotypes, both concluded that visual acuity is adult-like by 6 years of age. Using flanking bars with HOTV acuity stimuli also found adult levels of acuity around the age of 6 years. These results are provided in Tables 1.4, 1.5 and 1.6.

1.9 Contrast-modulated stimuli

It appears likely that a crowded contrast-modulated acuity test has the potential to be a superior tool for detection, and monitoring the treatment of, amblyopia. The current section discusses what contrast-modulated stimuli are and why this might be the case.

Most objects can be distinguished from their background because of a difference in luminance between them. For example, with commercially available visual acuity charts, the black optotype can be seen as separate from the white background due to luminance differences. Their structure is directly discernible in the Fourier spectrum of the image (Sutter et al., 1995; Mareschal and Baker, 1998; Schofield and Georgeson, 2003). These images are also known as luminance-defined, first-order or Fourier images. However, some objects are discernible from their background despite no change in mean luminance and are due to differences in contrast or texture. An example of this is a white noise image, whose local contrast is modulated at 1 cycle/degree. It contains no salient peaks of energy at 1 cycle/degree, so its spectrum remains flat (Schofield and Georgeson, 1999). A Fourier transform performed at a cross-section of a contrast-modulated image will result in a luminance profile of the image, with a mean luminance that is similar to the background's mean luminance; that is there is no luminance difference between them. Such images are known as contrast-modulated, second-order or non-Fourier images. Luminance profiles of the cross-section of standard luminance (L), luminance modulated (LM) and contrast modulated (CM) sample optotypes (in this case, "H") are shown in Figures 1.5, 1.6 and 1.7 respectively.

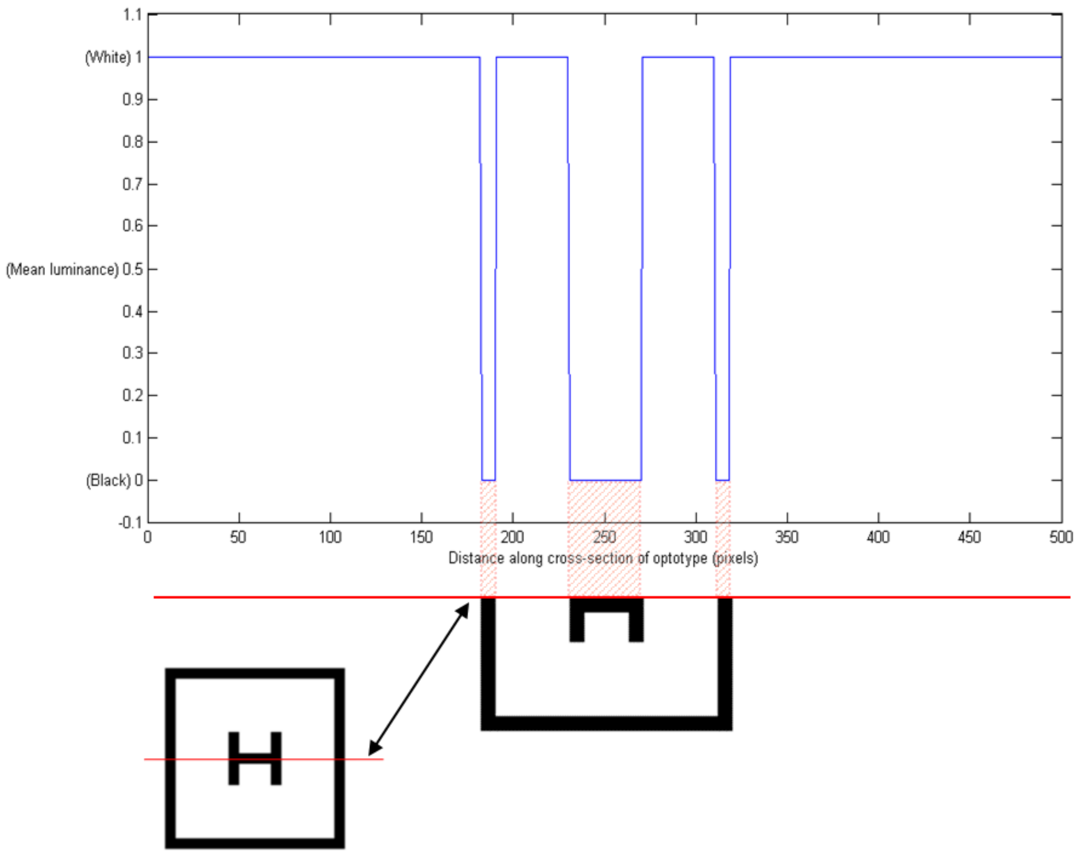


Figure 1.5: *Luminance profile of a cross-section of a black on white "H" surrounded by a box. The cross-section used is indicated by a red line. The x-axis shows the distance along the cross-section (measured in pixels) and the y-axis shows the luminance at that point with 1 being white and 0 being black. The optotype from the point of the cross-section down is shown below the x-axis, lined up with the position indicated on the x-axis to show how the stimuli corresponds to the luminance profile.*

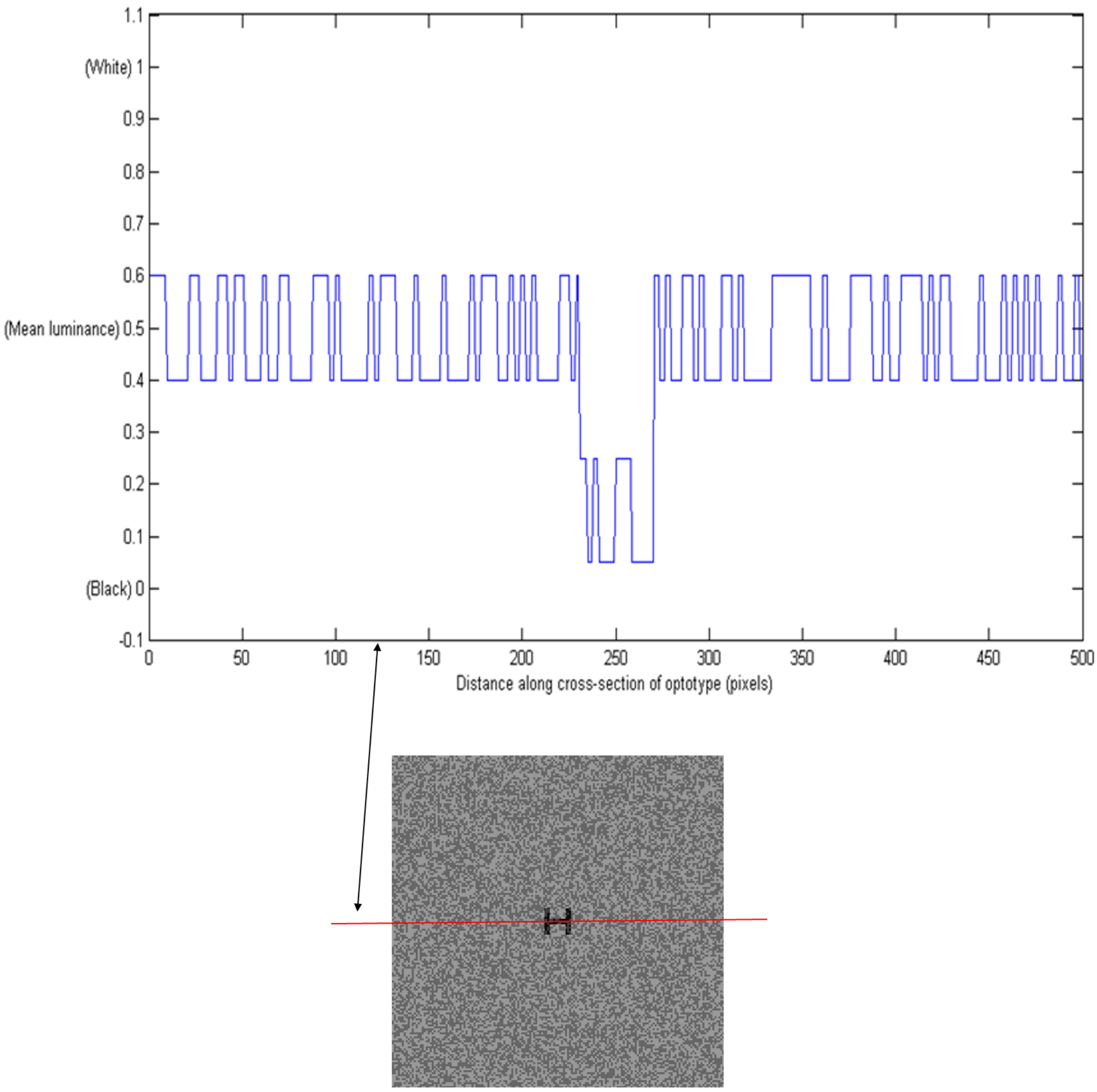


Figure 1.6: *Luminance profile of a cross-section of a decrement luminance-modulated isolated "H". The cross-section used is indicated by a red line. The optotype from the point of the cross-section down is shown below the x-axis, lined up with the position indicated on the x-axis to show how the stimuli corresponds to the luminance profile.*

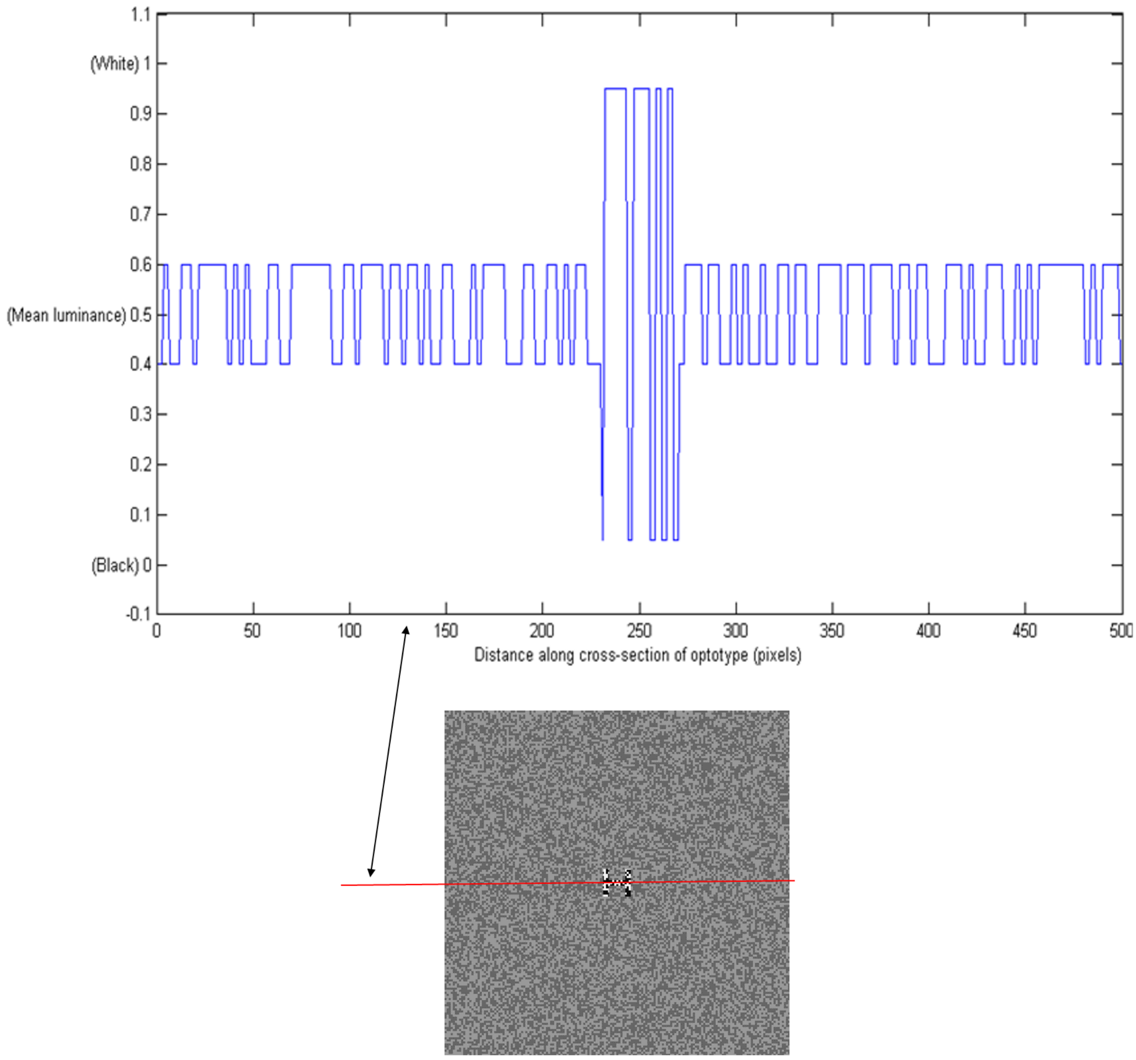


Figure 1.7: *Luminance profile of a cross-section of an increment contrast-modulated isolated "H". The cross-section used is indicated by a red line. The optotype from the point of the cross-section down is shown below the x-axis, lined up with the position indicated on the x-axis to show how the stimuli corresponds to the luminance profile.*

Current models of spatial vision rely heavily on outputs of linear or luminance-detecting mechanisms. Campbell and Robson (1968) described visual processing in terms of linear, Fourier type mechanisms or channels which respond to images according to their spatial frequency, orientation and direction of movement. Corresponding neural receptive fields have been identified at an early level of the visual cortex (V1) (Hubel and Wiesel, 1963, 1965; Tootell et al., 1998; Bakin et al., 2000; Larsson et al., 2006). However, these early neural receptive fields are not sensitive when the mean luminance remains constant. In order for objects defined by characteristics other than luminance to be detected, either higher-order cortical areas are engaged or more complex processing at a low level is required. Models for how luminance- and contrast-defined stimuli are processed can be divided into three groups: common mechanisms at all stages (Wong et al., 2005; Calvert et al., 2005), completely separate mechanisms (Chubb and Sperling, 1988; Mareschal and Baker, 1998; McGraw et al., 1999; Schofield and Georgeson, 1999, 2000; Ellemberg et al., 2003, 2006; Allard and Faubert, 2007; Sukumar and Waugh, 2007), and initially separate but common late mechanisms (Baker and Mareschal, 2001).

Psychophysical, VEP and brain imaging research has indicated that contrast-defined stimuli are processed in areas higher than V1, in particular V2 (Mareschal and Baker, 1998; Baker and Mareschal, 2001; Wong et al., 2005; Calvert et al., 2005; Sukumar and Waugh, 2007). Some research has shown that it is likely that contrast-defined stimuli are processed in a predominantly binocular region of the visual cortex (such as V2) rather than a predominantly monocular region (such as V1) (Hairol et al., 2010). This finding is supported by the deficits in processing contrast-defined stimuli seen in amblyopia (which is characterised by abnormal binocularity), which is additional to the well-known deficits in processing luminance-defined stimuli (Wong et al., 2001; Mansouri et al., 2005; Wong et al., 2005; Huang et al., 2006; Aaen-Stockdale et al., 2007).

Wong et al. (2001) investigated whether the detection loss to contrast-defined stimuli seen in amblyopes, is due to loss of input due to detection loss to luminance-defined stimuli, or whether there is an additional detection loss to contrast-defined stimuli. This was investigated using five amblyopic and three normal participants. They concluded that the loss of sensitivity to contrast-defined stimuli was greater than could be explained by the well-known loss of sensitivity to luminance-defined stimuli, particularly with one amblyopic participant who showed essentially no detection loss to luminance-defined stimuli but still had loss of sensitivity to contrast-defined stimuli seen in both the amblyopic and fellow eyes. This finding could only be explained by an additional loss of sensitivity to contrast-defined stimuli (Wong et al., 2001). Wong et al. (2005) investigated this further with six amblyopic participants, two strabismic participants with no visual acuity loss and two normal participants and concluded that amblyopes have a deficit at an early stage of extra-striate visual processing (V2), which is a primarily binocular region (Hubel and Livingstone, 1987). Mansouri et al. (2005) measured discrimination thresholds for both eyes with luminance- and contrast-defined stimuli for eight normal and eight amblyopic participants. They also concluded that the detection deficits to contrast-defined stimuli seen in both the amblyopic and fellow eyes of the amblyopes were not a consequence of the known sensitivity loss to luminance-defined stimuli.

As well as the additional loss of sensitivity to contrast-defined stimuli and exaggerated crowding seen in amblyopia, it has been suggested that crowding is even larger with contrast-defined, than luminance-defined, stimuli (Chung et al., 2007, 2008*a*; Formankiewicz et al., 2010; Hairol et al., 2010; Waugh et al., 2010; Hairol et al., 2013). Visual acuity with contrast-modulated square Cs is more susceptible to crowding, even with blur (up to two dioptres) (Waugh et al., 2010), whereas with luminance-modulated Cs, crowding reduced with blur (Waugh et al., 2010). With a detection task using large letters, a greater magnitude of crowding was found when using contrast-modulated letters than when using luminance-modulated letters with amblyopic observers (Chung et al., 2008*a*).

In summary, these findings indicate the potential for a contrast-modulated visual acuity chart to be more sensitive to amblyopia than any tests that are currently available. Contrast-modulated visual acuity tests in a format suitable for pre-literate children have not previously been investigated.

1.10 Rationale for this study

Crowding features are commonly used on pre-literate visual acuity charts to improve their sensitivity to amblyopia. The magnitude of acuity degradation due to crowding is greater for the amblyopic eye, so that inter-ocular differences will be enhanced. Although crowding features on visual acuity charts do improve their usefulness as a tool for diagnosing amblyopia, it is possible that a crowded contrast-modulated visual acuity test may be superior, as described in the previous section.

In order to investigate whether a contrast-modulated chart would be useful for aiding a clinician in diagnosing amblyopia, it is first necessary to determine normal adult spatial acuities for contrast-modulated optotypes suitable for use on a visual acuity chart designed for children. Crowding has been reported to be stronger with contrast-modulated, than with luminance-modulated stimuli in the laboratory (Chung et al., 2007, 2008*a*; Hairol et al., 2010; Formankiewicz et al., 2010; Waugh et al., 2010; Hairol et al., 2013). However the effects of flanking bars and optotypes on supra-threshold visual acuity measures using contrast-modulated stimuli are not yet known. In addition, work to find the optimal positioning to place the contour interaction or crowding features in a clinical chart needs to be investigated for both standard luminance, and contrast-modulated stimuli. These studies need to be conducted carefully and systematically on adults using robust psychophysical procedures, as well as modifying procedures for use in children. Measurement of visual acuity for these different types of optotypes in normal children can then be completed, before any future work can test their value in amblyopic children. Because a test for amblyopia would be most valuable if used in children (Flynn et al., 1998, 1999) and the developmental time-course for visual acuity for contrast-modulated optotypes is unknown, normal spatial acuity for contrast-modulated optotypes needs to be measured across age in normal children.

This project will investigate the potential applicability of crowded contrast-modulated optotypes in a clinical test for use in children, with the aim of potentially detecting amblyopia more effectively. Contour-interaction effects on visual acuity have been investigated with contrast modulated C targets (Hairol et al., 2013). It would be beneficial to investigate contour-interaction and crowding effects using non-letter optotypes also suitable for use in children, as the results of some research indicates that crowding may affect symbols differently to letters (Grainger et al., 2010).

In Experiment 1 visual acuity, as well as the magnitude of contour interaction and crowding, is measured over a range of target-flanker separations in normal adults, using letters and symbols from popular pre-literate visual acuity charts (specifically Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding Cards) with standard luminance (L), luminance-modulated (LM) and contrast-modulated (CM) optotypes. To facilitate comparisons between visual acuities obtained for different optotypes and stimulus conditions, thresholds were measured on adults using the method of constant stimuli, which provides information about the underlying psychometric function thresholds and slopes for visual acuity as well as controlling observer expectation and bias (Klein, 2001). This method is appropriate to use on normal adults in a research laboratory setting and is similar to the method used in other similar research (for example: Hess and Jacobs, 1979; Leat et al., 1999; Tripathy and Cavanagh, 2002; Hariharan et al., 2005; Wong et al., 2005; Hairol et al., 2013). However, the method of constant stimuli is lengthy and not appropriate to use clinically. The staircase method is quicker and preferable, especially when testing young children. A suitable staircase method was established to use in Experiment 2 with normal children. Results of visual acuity measures obtained with normal adults using this staircase method and those obtained using the method of constant stimuli, are presented and shown to compare well. Experiment 2 then investigates visual acuity for crowded and uncrowded versions of the standard luminance (L), luminance-modulated (LM) and contrast-modulated (CM) versions of the four charts from Experiment 1 with normal children aged 3 to 16 years old, in order to determine normal thresholds, particularly for contrast-modulated stimuli, with development.

Chapter 2

Experiment 1: Normal adults*

2.1 Introduction

Visual acuity for a target optotype measured with surrounding features is worse than that measured without surrounding features (Flom, Weymouth and Kahneman, 1963; Hess and Jacobs, 1979; Leat et al., 1999; Formankiewicz and Waugh, 2013). This negative spatial interaction effect on target resolvability is generally referred to as "crowding" which has been found to be greater in amblyopes than in individuals with normal vision (Mayer and Gross, 1990; Morad et al., 1999; Hess et al., 2001; Levi, Hariharan and Klein, 2002; but see Stuart and Burian, 1962; Flom, Weymouth and Kahneman, 1963). Contour interaction was proposed to be a sub-component of crowding (along with attention and eye movements) by Flom, Weymouth and Kahneman (1963) and refers to the detrimental effects of nearby contours (such as bars) that surround the target. In crowding, detrimental effects are produced by surrounding the target with more complex features similar to the target itself, such as other letters. Alternatively, contour interaction and crowding have been proposed to be distinct entities (Pelli, Palomares and Majaj, 2004). However, clinically, boxes and neighbouring optotypes have been incorporated into most visual acuity charts to introduce "crowding" effects (Atkinson et al., 1988; Simmers et al., 1997; Schlenker et al., 2010; McGraw and Winn, 1993; McGraw et al., 2000) to improve the sensitivity of visual acuity measurement in detecting amblyopia.

*Part of this Chapter has been published in modified form as: Lalor, S.J.H., Formankiewicz, M.A. and Waugh, S.J., (2016). 'Crowding and visual acuity measured in adults using paediatric test letters, pictures and symbols.' *Vision Research*, **121**, 31-38.

A larger magnitude of contour interaction and crowding can be found when using contrast-modulated (CM) than luminance-modulated (LM) target letters and surrounds (Chung et al., 2008*b*; Hairol et al., 2013). Additionally, amblyopes appear to have a specific detection loss to contrast-modulated (CM) stimuli (Wong et al., 2001, 2005; Mansouri et al., 2005; Chung et al., 2008*b*). These two factors indicate that crowded contrast-modulated (CM) optotypes could be useful for the detection of amblyopia. So, it would be beneficial to investigate crowding with CM optotypes suitable for pre-literate visual acuity tests, first in normal adults and then in normal children (aged 3-16 years).

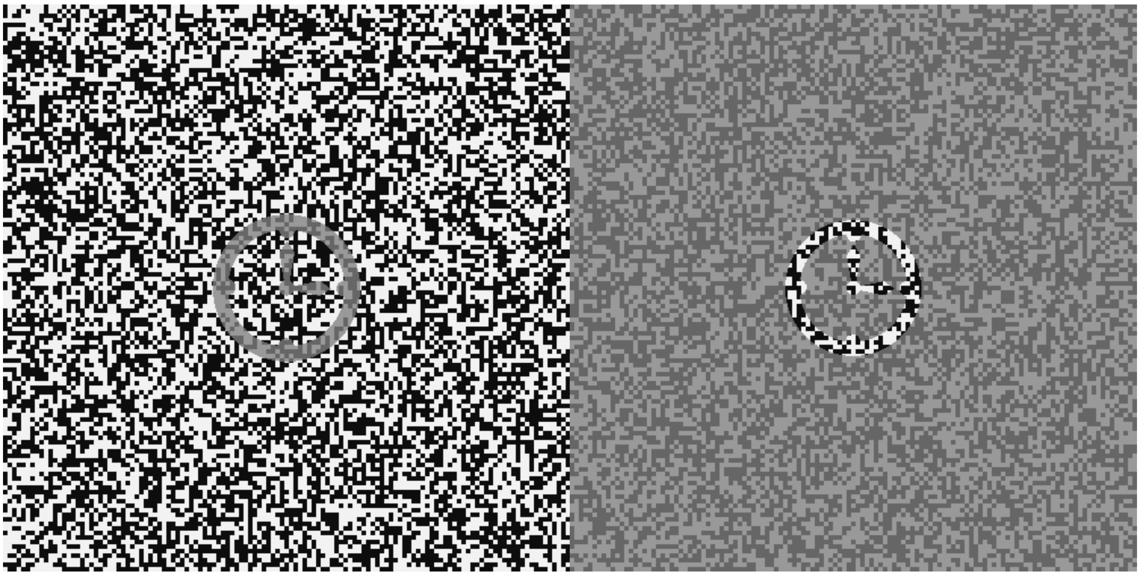


Figure 2.1: *(a) Decrement (left) and (b) increment (right) contrast modulated (CM) Kay Picture "clock" optotypes.*

Commercially available visual acuity tests have black optotypes (minimum luminance) on a white (maximum luminance) background, i.e. the optotypes are constructed using luminance-defined (L) decrements. Contrast-modulated (CM) optotypes, have background noise (background) and optotype noise (figure), both modulated about the mean luminance. The intuitive configuration would be for the optotype to be presented as an increment in contrast. That is, a high contrast "object" would be presented against a low contrast "background". Luminance-modulated (LM) optotypes, to be like standard acuity charts, would intuitively be presented as a decrement in luminance (i.e. a dark optotype on a light background). The increment CM stimulus condition, as well as appearing most natural in terms of "figure-ground" relationships (see Figure 2.1), has also been used in previous research (Chung et al., 2008*b*; Hairol et al., 2013).

The position of crowding features on commercially available acuity tests is normally specified in optotype widths measured between the edges of the target and the surrounding features (Hyvärinen et al., 1980; McGraw and Winn, 1993) and is based primarily on the findings from Flom, Weymouth and Kahneman (1963), who reported that performance on a Landolt C task is maximally degraded when bars are placed at an edge-to-edge distance of 0.4 optotype width (or 2 stroke widths) away. Crowding features, such as other letters, bars or a box, on children's visual acuity tests are generally placed at 0.5 optotype widths away from the target letter or line of symbols, pictures or letters (Atkinson et al., 1988; Holmes et al., 2001; Jones et al., 2003; Vision in Preschoolers (VIP) Study Group, 2005; McGraw and Winn, 1993). A separation of 1 optotype width has been used on the Sonsken chart (Salt et al., 2007), which follows the design of the Bailey-Lovie chart (Bailey and Lovie, 1976). However, exactly which units of separation should be used to specify separation between the target optotype and neighbouring features to obtain best consistency of results across chart, remains unclear. Some researchers studying foveal vision (for example: Simmers et al., 2000; Hess et al., 2001; Bedell et al., 2013) have suggested that minutes of arc, rather than optotype-widths or stroke-widths may be more suitable. Other researchers have suggested that the distance measured between the target optotype and the flanking crowding features should be measured from the centre of the target optotype to the centre of the flankers (for example: Pelli, Palomares and Majaj, 2004; Chung, 2016), rather than edge-to-edge.

"Crowded" tests are recommended for childrens' vision screening programs (Solebo et al., 2013; UK National Screening Committee, 2013; Cotter et al., 2015); specifically single optotypes with crowding features are considered "best practice" for children less than 6 years of age (Solebo et al., 2013; UK National Screening Committee, 2013; Cotter et al., 2015). It has been suggested that the "crowding" effect is likely to be enhanced if "crowding" features are more similar to the target optotype (Kooi et al., 1994; Song et al., 2014) and positioned closer to the target optotype (Formankiewicz and Waugh, 2013; Song et al., 2014) than the current closest commercially available visual acuity test of 0.5 optotype widths (Atkinson et al., 1988; Holmes et al., 2001; Jones et al., 2003; McGraw and Winn, 1993; Vision in Preschoolers (VIP) Study Group, 2004). The effects of the position of crowding features on visual acuity measured with a single picture or symbol optotypes have not yet been investigated.

Variability in the legibility of optotypes used in pre-literate visual acuity tests has previously been reported when tested with adults with full refractive correction (Candy et al., 2011). Differences in legibility mean that visual acuities measured could be affected by the choice of optotype. Variations in the impact of crowding features may also depend on optotype choice, which may have implications on the visual acuity measured, as does the number of response choices made (Carkeet, 2001; Klein, 2001).

In Experiment 1, visual acuity using standard luminance (L), luminance-modulated (LM) and contrast-modulated (CM) letters and symbols is measured. The effects of crowding features on visual acuity for a range of target-flanker separations using optotypes presented on their own and together with a surrounding box or flanking letters, are calculated. Displaying one at a time, instead of four or five in a line as is common on commercial visual acuity tests, reduces the influence of factors such as eye movements (Flom, Weymouth and Kahneman, 1963). Some research studies have used flanking bars rather than a surrounding box (for example: Flom, Weymouth and Kahneman, 1963; Flom, Heath and Takahashi, 1963; Simons, 1983). Herzog et al. (2015) suggested that "grouping" of crowding features, such as that which may occur when four extended bars create a box, can reduce the effects of crowding even though physically, more contours exist for a box. A control experiment was conducted to investigate contour interaction when bars, instead of a box, were used as crowding features with Kay Pictures and Lea Symbols; bars, boxes and letters were used with HOTV optotypes, over a range of separations to assess the role of contour interaction and crowding. A test in which letters are surrounded with flanking letters (as in Cambridge Crowding test) was included because it has been suggested that the crowding in acuity tasks may be more effective if the flankers are more similar to the target (Formankiewicz and Waugh, 2013; Song et al., 2014).

The results of Experiment 1 will determine the optimum position to place surrounding features to optimise contour interaction and crowding in Experiment 2 (with normal children). The extent of contour interaction and crowding is assessed for different single optotypes and stimulus types, and the question of which unit of separation best reflects consistent contour interaction or crowding across tests is answered.

2.2 Specific aims

In the first pilot experiment the aim is to select four Kay Pictures from the original set of eight, to give the same number of alternatives, as is provided in the other (Lea Symbols, HOTV and modified Cambridge Crowded) visual acuity tests. For contrast-modulated noise (CM) optotypes, a mean luminance background and optotype is required, however in standard clinical charts, black letters on a white background is used. For better comparison of LM and CM acuities, it is important to use a similar mean luminance noisy background, however more natural viewing configurations would be to view a decremental optotype for LM stimuli, but an incremental optotype for CM stimuli (see methods section). In the second pilot experiment the effects of incremental versus decremental optotypes on visual acuity and crowding is examined to understand the effects that this choice may have on clinical measures.

In the main Experiment, the aims are then to

1. compare visual acuity estimates using single target presentations of optotypes from different pre-literate visual acuity tests with standard luminance (L), as used for visual acuity measurements clinically), luminance-modulated (LM) and contrast-modulated (CM) optotypes, and

2. determine the optimum positioning of crowding features on single target presentations and to determine which units produce most consistent (or less variable) estimates of the spatial extent of contour interaction/crowding across test.

2.3 Method

2.3.1 Apparatus

The presentation and control of visual stimuli used a custom-written Matlab program (MathWorks™, Natick, USA) on a Dell Precision T3400 computer driving a Cambridge Research Systems ViSaGe (Visual Stimulus Generator). The monitor was calibrated and gamma corrected using 768 estimates from the range of possible luminance outputs from each electron gun using an OptiCal photometer (Cambridge Research Systems). Each gun's non-linearity was gamma-corrected to produce a linear response profile. For all experiments, the stimuli were displayed on a Mitsubishi Diamond Pro 2070SB CRT monitor. The screen resolution was set to the highest possible spatial resolution (1104x828 pixels) and the frame rate was set to 120Hz, the highest frame rate compatible with the aforementioned spatial resolution. The pixel size was 0.36mm, which subtended 1.24 minutes of arc at a 1m viewing distance. The monitor was turned on for at least 60 minutes before data collection started, to ensure that the luminance output was stable. This was determined by taking luminance readings every second for 2.5 hours as the monitor "warmed up" (see Appendix A).

2.3.2 Participants

All experiments were carried out in accordance with the Code of Ethics of the World Medical Association in the Declaration of Helsinki World Medical Association (2001) and approval of the experimental protocol was obtained from the appropriate Anglia Ruskin University Human Research Ethics Committee. All participants provided written informed consent before the experiments were conducted and after the nature and consequences of the study were explained. Participants were recruited through personal contacts and posters displayed in the university.

Participants were all adults (mean age: 23.8 years, range 22-25 years) wearing full refractive correction (full spectacle correction with best vision sphere of -2.25D to $+0.75$D spectacle lenses) with visual acuity of 6/5 or better in each eye (for full details see Table 2.1). Stereoacuity was 30 arcsec or better, measured with the Dutch Organisation for

Applied Scientific Research (TNO) test for stereoscopic vision (Lameris Ootech, Ede, The Netherlands). It was important to ensure that participants had normal binocular vision, as crowding can be different in individuals who have disrupted binocularity (Greenwood et al., 2012). Viewing was always monocular using the dominant eye, which was established using the Miles Test (Miles, 1930). One participant (SL) was the author and took part in all experiments in this chapter. All other participants were naïve to the aims of the experiments. Four normal adults (AM, IH, JEB and SL) participated in the Kay Picture optotype selection pilot and two normal adults (JEB and SL) participated in the figure-ground pilot experiment. IH was an experienced psychophysical observer who only participated in the Kay Picture optotype selection pilot. Two participants (NS and SL) also participated in the bars versus box control experiment. Only a small number of participants is required for the experiments in this chapter, as results aim to establish normal representative visual functions by using a high number of trials. Campbell and Robson (1968) have shown this by establishing the classic contrast sensitivity function study using only two participants and a high number of trials.

Table 2.1: *Information about the normal adult participants who took part in Experiment 1.*

Participant	**Ethnicity**	**Spectacle refraction**	**Visual Acuity**	**Stereoacuity**
AM	Caucasian	R: $-1.00/-0.25\times140$ L: $-1.00/-0.25\times170$	6/4 6/4	15” arc
JEB	Caucasian	R: $+0.50$DS L: $+0.75$DS	6/4 6/4	15” arc
KM	Asian	R: -2.25DS L: -1.75DS	6/5 6/4	15” arc
NS	Caucasian	R: $-0.25/-0.25\times15$ L: $-0.25/-0.25\times80$	6/5 6/5	15” arc
SL	Caucasian	R: -0.75DS L: $-0.75/-0.25\times80$	6/5 6/4	30” arc

2.3.3 Stimuli

Choice of optotypes

The optotypes used in this study (see Figure 2.2) were derived from four popular pre-literate visual acuity tests: Kay Picture Test (Product Ref: KAY-KPTLV, BiB Ophthalmic Instruments, Stevenage, UK) (Kay Pictures Ltd, Tring UK) (Kay, 1983), Lea Symbols

(Good-Lite, Illionois, USA) (Hyvärinen et al., 1980) , HOTV (Precision Vision, Illionois, USA) (Lippmann, 1971) and Cambridge Crowding test (Clement Clarke, Harlow, UK) (Atkinson et al., 1988). The original tests comprise different numbers of optotypes. The Lea Symbols and HOTV charts use four optotypes. The Cambridge Crowding test uses five target optotypes (H, O, T, V and X), four being the same as in the HOTV chart and so, for the purposes of this study, the "X" was not used in order to enable direct comparison. The Kay Picture Test has eight optotypes (apple, boot, clock, cup, duck, fish, house and truck). To equalise the guess rate (at 1 in 4) across tests, 4 of the 8 optotypes in the Kay Picture test were chosen in the Kay Picture pilot experiment. The choice was made by considering visual acuities obtained and contour-interaction effects generated.

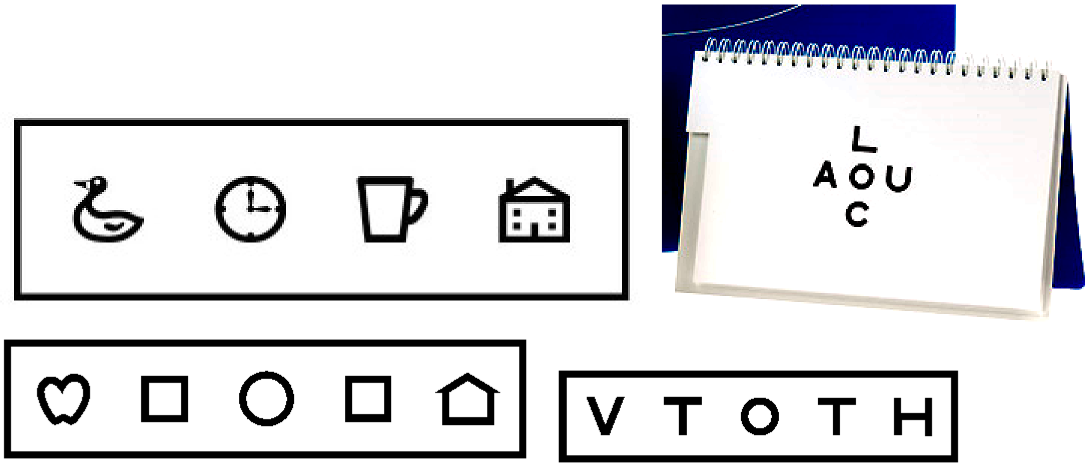


Figure 2.2: *Visual acuity tests used in these experiments shown in their commercially available crowded form. Top left is the Kay Picture test, top right is the Cambridge Crowding Cards, bottom left is the Lea Symbols test and bottom right is the HOTV test.*

Optotypes were displayed individually without crowding features ("isolated"), and with contour interaction or crowding features at a separation of 0 (abutting), 1, 2, 3, 4 and 5 stroke-widths away, measured from edge-to-edge. Separation is defined as the distance between the optotype edge and the inner edge of the crowding feature(s). A stroke-width refers to the width of the line that "drew" both the optotype and the box (this was always constant). For all experiments in this study a single target optotype (see Figure 2.3) was surrounded by a box for the Kay Pictures, Lea Symbols and HOTV tests, and by flanking letters (A, C, L and U in a random configuration) for the Cambridge Crowded test.

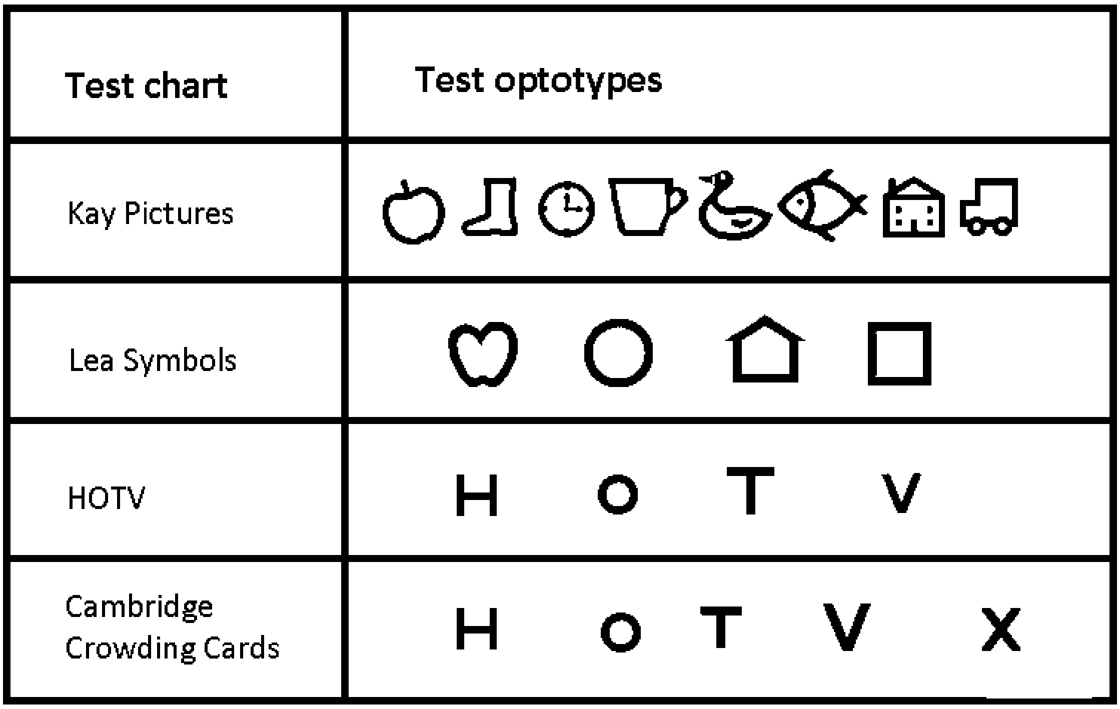


Figure 2.3: *The optotypes in the pre-literate visual acuity tests used.*

Defining separation

The distance between the target optotype and the crowding features (often flanking contours) can be measured in many different ways. In these experiments the target-flanker distance has been specified in stroke widths from the outside edge of the optotype to the inside edge of the crowding feature/s (edge-to-edge) (see the rationale in Takahashi, 1968; Siderov et al., 2012). The most common methods of specifying separation are: multiples of the width of the optotype (optotype widths), multiples of width of the strokes (lines) that make up an optotype (stroke widths), the width of the gap in a “C” or between limbs in an “E” (gap widths, which are equivalent to stroke-widths if the letters are created on a 5×5 stroke width grid), and minutes of arc (arcmin). Units of stroke-width are used to quantify visual acuity for all tests. The same cannot be said for optotype size (Bailey and Lovie-Kitchin, 2013), which varies from 5 stroke widths per optotype (HOTV and Cambridge Crowding test) to 10 stroke widths per optotype (Kay Picture test).

Creation of computerised tests

There is evidence that computerised vision testing is directly comparable to results from paper charts in terms of repeatability, accuracy and testing time (Ehrmann et al., 2009; Shah et al., 2012). In order to produce computer-generated tests, every size of every optotype from the printed (standard luminance, or L) versions was carefully measured to obtain information about physical sizes of the optotypes for particular acuity scores, (for measured sizes, see Appendix B). The printed optotypes were scanned and converted to pure black and white (i.e., greys were removed), and cleaned up using GIMP (GNU Image Manipulation Program, Berkley, USA). These images were then converted into Matlab (MathWorks^{TM}, Natick, USA) matrices. The matrices were scaled so that stroke-width varied from 1 to 26 pixels. This size range allowed for a large range of stimulus sizes to fit on the screen. A custom-written Matlab (MathWorks^{TM}, Natick, USA) program ensured that all stimuli were constructed in multiples of whole numbers of pixels so that sizes actually displayed were recorded exactly (i.e. the size closest to the intended size, which was always very close, was converted to logMAR and recorded in the results file as the size shown, not as the intended size).

The physical size of the optotype presented on the screen was based on the viewing distance of the participant and the required logMAR size. Optotypes, with and without crowding/contour interaction features, were displayed against a square background that covered the height of the screen. The rest of the screen area was at the mean luminance of the background. For example, for the noiseless decrement L condition, the stimulus (optotype) is black (0.6cd/m^2) on a white square background (102cm/m^2) with the rest of the screen at the mean luminance of the background (white). For stimulus conditions with noise, the rest of the screen was a single luminance that was an average of the two luminances in the background. The single luminance that covered the rest of the screen covered the whole screen for exactly 500ms between stimulus (optotype) presentations, which prevented immediate shape change from providing cues about which letter or symbol had just appeared and allowed time for the computer to load all frames for the next dynamic presentation of a stimulus.

Creation of noise stimuli

Dynamic noise was used to avoid any consistent local luminance cues from occurring, which is especially important when generating CM stimuli (Smith and Ledgeway, 1997). For each stimulus, different noise pages were created and randomly cycled during stimulus display to create dynamic noise. If too few noise pages are used, then unintentional consistent spatial patterns can occur. However, too many noise pages can computationally slow down the presentation rate. Direct experimentation suggested that having ten noise pages was a suitable compromise. The noise page duration (the number of video frames until a new noise page was displayed) was set to four temporal frames or 33ms. For stimuli created from a noise background, the optotype was added to, or multiplied by, binary white noise to produce the luminance-modulated noise (LM) and contrast-modulated noise (CM) stimuli, respectively. The stimuli can be mathematically expressed as:

$$I\left(x,y\right)=I_0\left(1+nN\left(x,y\right)+mnM\left(x,y\right)N\left(x,y\right)+lL\left(x,y\right)\right) \tag{2.1}$$

where "I_0" is the mean luminance, "$M(x,y)$" is the contrast modulating signal, "$L(x,y)$" is the luminance modulating signal, and "$N(x,y)$" is binary white noise. Amplitudes "l", "m" and "n" define the modulations of the luminance, contrast and background noise, respectively (Schofield and Georgeson, 1999). When "l" is zero, the noise will be contrast-modulated. In LM conditions "l" was set to 0.7, in CM conditions "m" was set to be 3.5 and in both LM and CM conditions (the conditions with noise), noise amplitude "n" was fixed at 0.2, conditions where there was no noise "n" was set to 0. These values produce high visibility optotypes for visual acuity testing. Pixel-by-pixel luminance profiles of the stimuli are shown Figures 1.5, 1.6 and 1.7 in Section 1.9. Figure 2.4 shows the amplitude difference spectrum (ADS) between the direction containing the gap in the square C and the perpendicular direction without a gap. The difference in Fourier spectra or ADS was calculated in two directions from an average of 500 images.

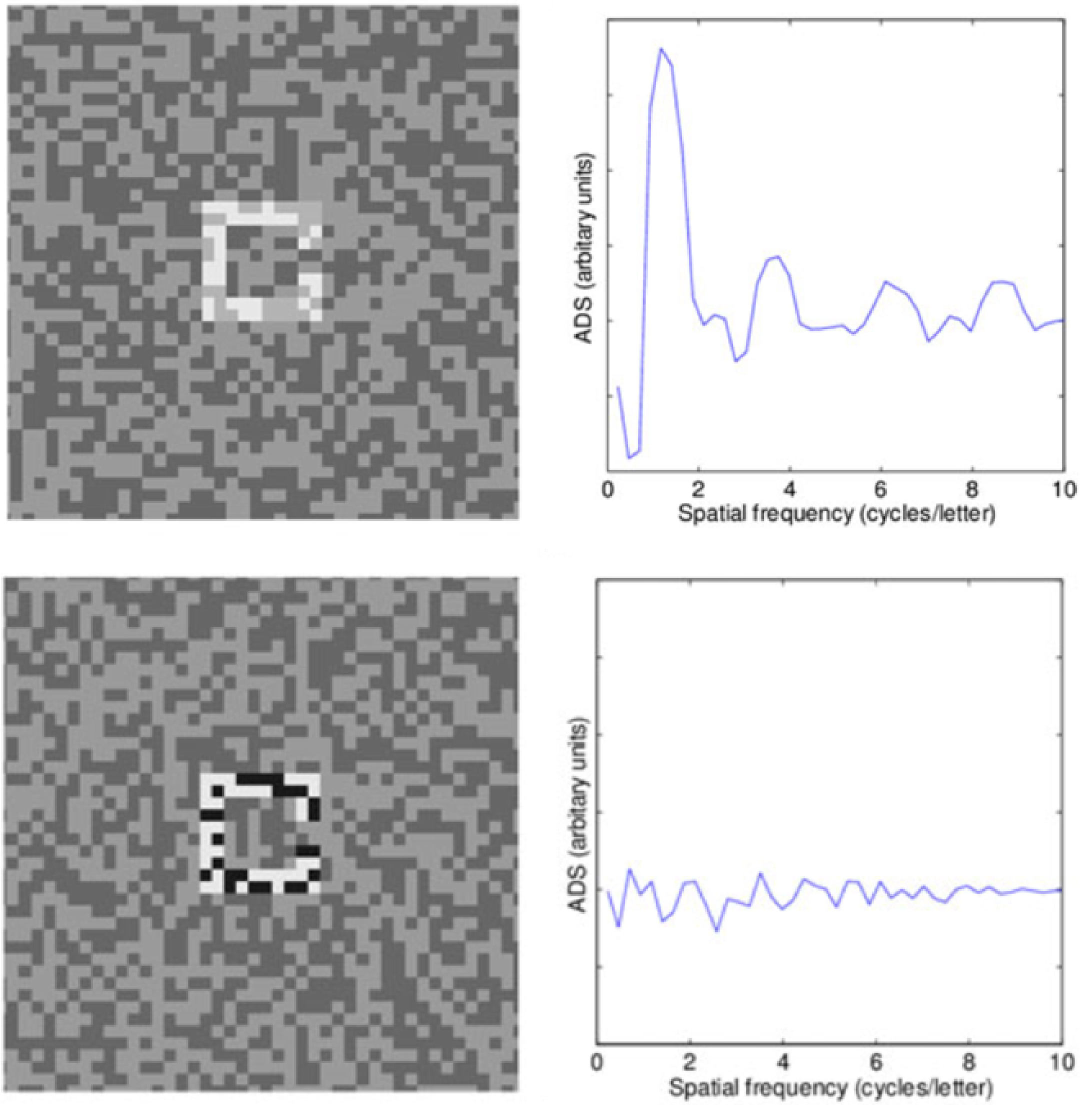


Figure 2.4: *Square Cs are shown on the left and the amplitude difference spectrum (ADS), or difference in the Fourier spectra, for the images are shown on the right. The difference in Fourier spectra or ADS was claculated in two directions (with and without the gap) from an average of 500 images. These are shown for luminance modulated (LM) stimuli (top) and contrast modulated (CM) stimuli (bottom). The images are adapted from Hairol et al. (2013).*

2.3.4 Procedure

The method of constant stimuli (Urban, 1910) combined with forced-choice psychophysics was employed as it gives detailed information about thresholds and slopes of the underlying psychometric functions for visual acuity, and minimises observer expectation and bias (Klein, 2001). This method is appropriate to use on normal adults in a research laboratory setting and similar to that used in other studies (Hess and Jacobs, 1979; Leat et al., 1999; Tripathy and Cavanagh, 2002; Hariharan et al., 2005; Wong et al., 2005; Hairol et al., 2013). A self-paced four- or eight-alternative forced-choice (4AFC or 8AFC) procedure was used with the method of constant stimuli. Participants were required to indicate which one of the four, or eight, optotypes was presented onto the screen. No feedback was given to the participants about the accuracy of their response. In each trial, participants had unlimited time to respond to be similar to clinical measures of acuity. However, prompt answers were encouraged. In each experimental run there were 100 trials, during which a single target optotype was randomly selected from seven size levels (separated by 0.1 logMAR), for the chosen test. From these seven levels, responses ranged from guess rate (12.5% or 25% correct performance for the 4AFC and 8AFC respectively) to 100% correct. Testing was monocular with the dominant eye occluded with a black patch. Participants viewed the screen from a distance of 4.5 (for CM stimuli) or 9m (for L and LM stimuli) except for with one participant (AM) where the distance had to be increased to 11.5m for L and LM stimuli to ensure a sufficient range of sizes. Participants indicated which optotype they thought they had seen by pressing an appropriate response button. Each participant also completed practice sessions before data collection began to ensure they were familiar with the task and the optotypes. For all experiments (pilot, main and control) data were counterbalanced in order across the relevant stimulus dimensions to even out practise and fatigue effects. Ambient light was on to make testing of young children easier. This was done for all experiments to ensure consistency.

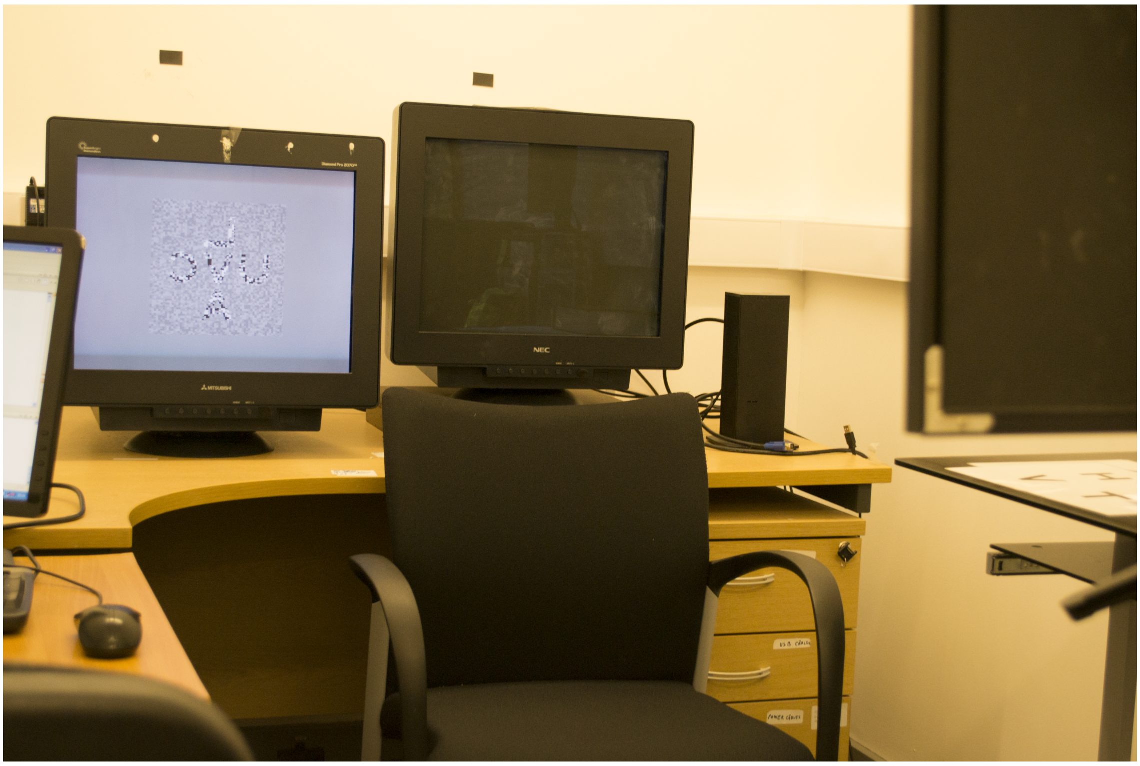


Figure 2.5: *The experimental setup at 4.5m showing the chair that the participant sat on, the mirror (top right) and the left CRT computer monitor (showing CM stimuli). The edge of the TFT monitor on the left is the control unit, the right CRT monitor was used for other experiments only and the ViSaGe system is on the right of the CRT monitors. The mirror was moved further from the chair and computer monitor for 9m.*

Kay Picture pilot optotype selection

A pilot experiment was carried out to select four out of the eight optotypes used in the commercially available original Kay Picture test in order to compare the results for Kay Pictures with results from other tests in Experiment 1. The target optotype was displayed individually without any crowding features (isolated condition) and flanked by a box placed 1 and 5 stroke-widths away from the target (see Figure 2.6). Only one target-flanker separation was used in each experimental run. In each experimental run, data for the individual optotypes were kept separately, so that visual acuity for each optotype could be determined. Data from 16 (for 2 participants) or 32 (for 2 participants) experimental runs per crowding condition were averaged (allowing for 200 or 400 trials to be accumulated for each of the 8 original optotypes).

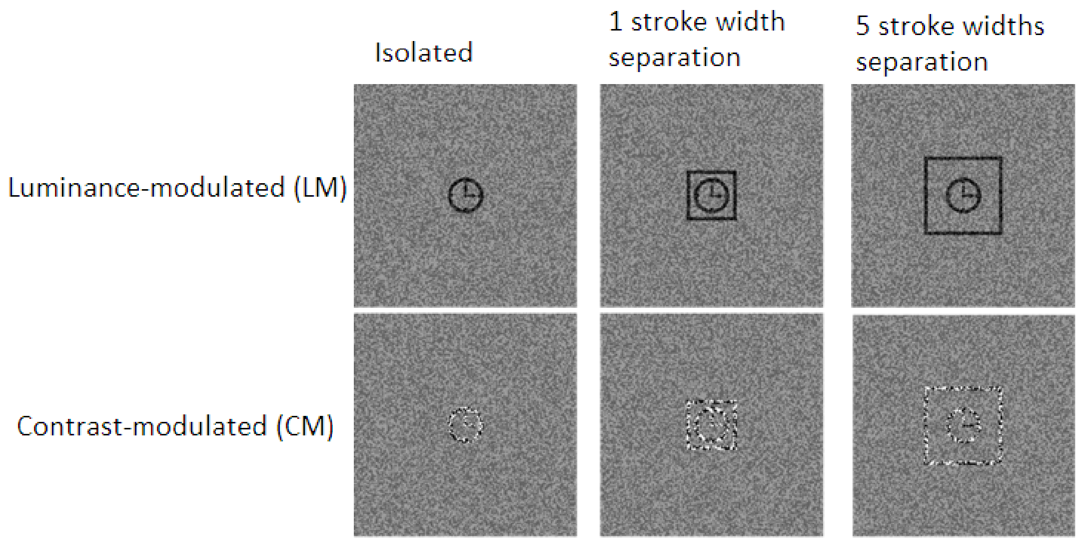
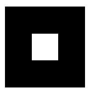
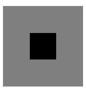
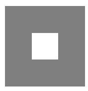
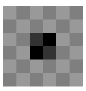
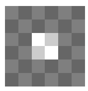
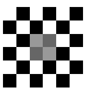
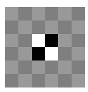


Figure 2.6: *Examples of the configurations used in the Kay Picture optotype selection pilot.*

Figure-ground configuration pilot

A method of constant stimuli with a self-paced 4-alternative forced-choice (4AFC) procedure was used to collect data on two participants about whether choice of natural configurations for L, LM and CM stimuli are suitable for use in the main experiment. Data were obtained for eight figure-ground stimulus conditions (see Table 2.2) and 7 separations (i.e. isolated, 0, 1, 2, 3, 4 and 5 stroke widths). The stimuli were four Kay pictures, Lea Symbols and HOTV optotypes.

Table 2.2: *This table shows all the possible stimulus presentations with a description and a demonstration of the stimulus presentation in picture form. The images show what a square on a background would look like. "Noisy" stimuli are shown here with static noise but in the experiments the noise was dynamic.*

	Decrement	Increment
Noiseless	(1) Black on white 	(2) White on black 
	(3) Black on mean luminance 	(4) White on mean luminance 
Noisy	(5) Black on mean luminance 	(6) White on mean luminance 
	(7) Low contrast on high contrast 	(8) High contrast on low contrast 

Main experiment

The target optotype was displayed individually without any crowding features (isolated condition) and with flankers placed at separation of 0 (abutting), 1, 2, 3, 4 and 5 stroke-widths away from the target for L, LM and CM stimulus optotypes and for Lea, Kay, HOTV and Cambridge Crowding tests.

2.3.5 Analysis

For each participant and condition, data for up to 32 experimental runs were collated in Microsoft Excel and averaged. In IgorPro (WaveMetrics Inc., USA), the averaged data were fit with a Weibull function (Weibull, 1951), as has previously been applied in letter acuity studies (Pelli and Hoepner, 1989; Alexander et al., 1997; Plainis et al., 2007; Zhang et al., 2007; Watson and Ahumada, 2012; Formankiewicz and Waugh, 2013), to derive the threshold for optotype discrimination (or visual acuity) and slope value, which provides information about the sensitivity of the estimated threshold (Strasburger, 2001). The Weibull function can be used to approximate the pscyhometric function (Mortensen, 2002) and is expressed by the formula:

$$P_{correct}(s) = 1 - (1 - g) \times exp[-10^{\beta(s-th)}] \tag{2.2}$$

where g is the guess rate (12.5% with the 8AFC procedure and 25% with the 4AFC procedure), β is the slope of the psychometric function, s is the target size in logMAR and th is the estimated discrimination threshold or visual acuity, corresponding to the logMAR which was 67.8% and 72.4% correct, for 8AFC and 4AFC paradigms, respectively.

Statistical analyses of the data were performed using a repeated measures Analysis of Variance (ANOVA) with a Huynh-Feldt correction for the violation of sphericity assumption. When appropriate, for example in determining crowding extent, post hoc analyses were carried out with a Tukey HSD test.

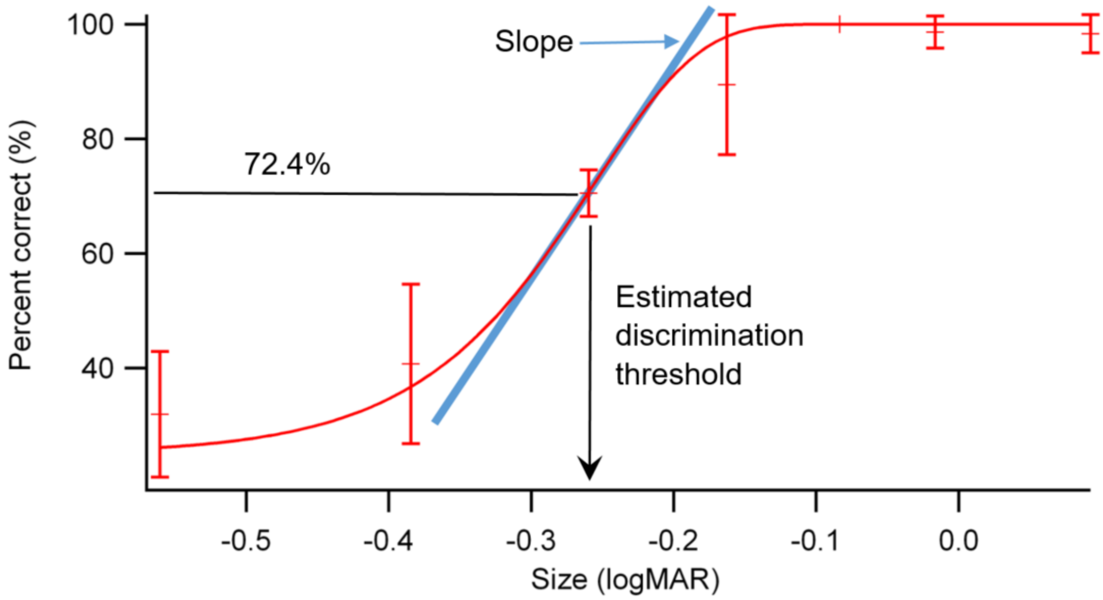


Figure 2.7: *Example data fitted with a Weibull function (using Equation 2.2), showing the slope of the psychometric function and the estimated discrimination threshold.*

2.4 Results

2.4.1 Pilot Experiment 1: Kay Picture optotype selection

Visual acuity data for the eight Kay picture optotypes are shown in Figure 2.8. A 2 (stimulus) × 3 (separation) × 8 (optotype) Repeated Measures ANOVA (shown in Table 2.3) was conducted on these data. There was a significant effect of stimulus type on visual acuity [F(1,3)=6937; p<0.0001]. CM visual acuity thresholds were on average 0.62±0.01 logMAR worse than LM visual acuity thresholds. The effect of stimulus type did depend on optotype choice [F(7,21)=4.4, p=0.004]. The range of acuities across optotype was larger with LM (0.24±0.11 logMAR) than with CM (0.15±0.08 logMAR) stimuli. Tukey posthoc pairwise comparisons showed no significant difference in visual acuity measurements between pairs of CM optotypes ($p > 0.05$) but with LM optotypes the acuity measured with the "duck" was significantly better than all other optotypes except the "boot" ($p > 0.05$) and the "fish" ($p > 0.05$). Clinically one would not use different symbols with different stimulus types so collapsing across stimulus type, the highest (worst) acuities were obtained with the "apple" and the lowest (best) acuities were obtained with the "duck"; these results were also found by Anstice et al. (2017*b*). Planned comparisons showed a significant difference between isolated visual acuities and those obtained with a box at a separation of 1 stroke width [F(1,3)=17, p=0.027] but not 5 stroke widths [F(1,3)=6.5, p=0.083]. The magnitude of contour interaction was calculated by subtracting the isolated optotype visual acuity from the visual acuity measured with a surrounding box at 1 stroke-width (Figure 2.9) to help select which symbols crowd most effectively.

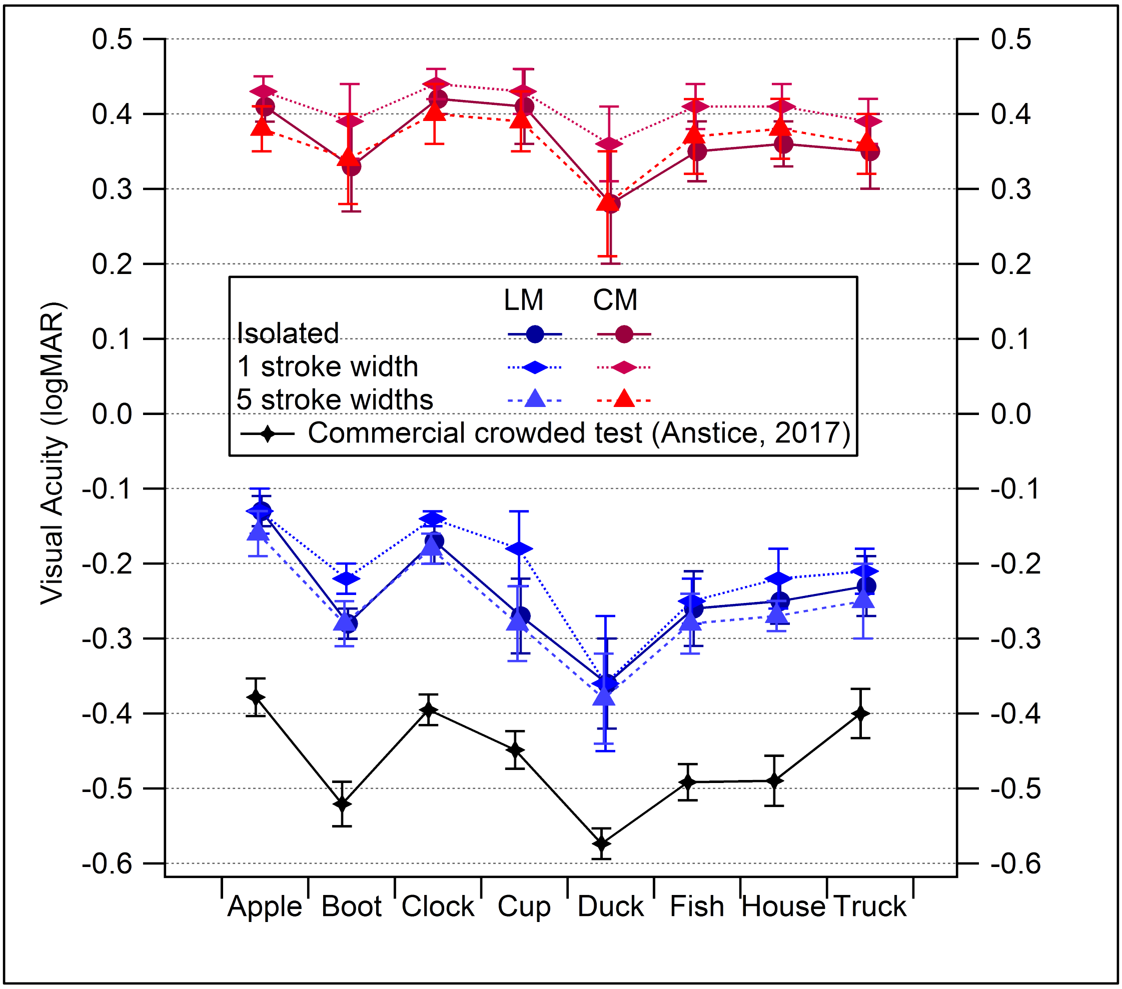


Figure 2.8: *Visual acuity measurements averaged across all participants for LM and CM versions of each of the Kay Picture test optotypes. The error bars indicate ±1SE. Visual acuity data for each optotype measured using the commercially available version of the crowded Kay Picture test from Anstice et al. (2017*b,a*) is also shown.*

Contour interaction on average was weak with the “duck”, “apple” and “fish” for LM optotypes and with the “apple” and “cup” for CM optotypes. Clinically one would not use different symbols with different stimulus types so collapsing across stimulus type (LM and CM), the strongest (most) contour interaction was obtained with the “boot” (mean 0.06±0.01 logMAR) and the weakest (least) contour interaction was obtained with the "apple" (mean 0.00±0.01 logMAR).

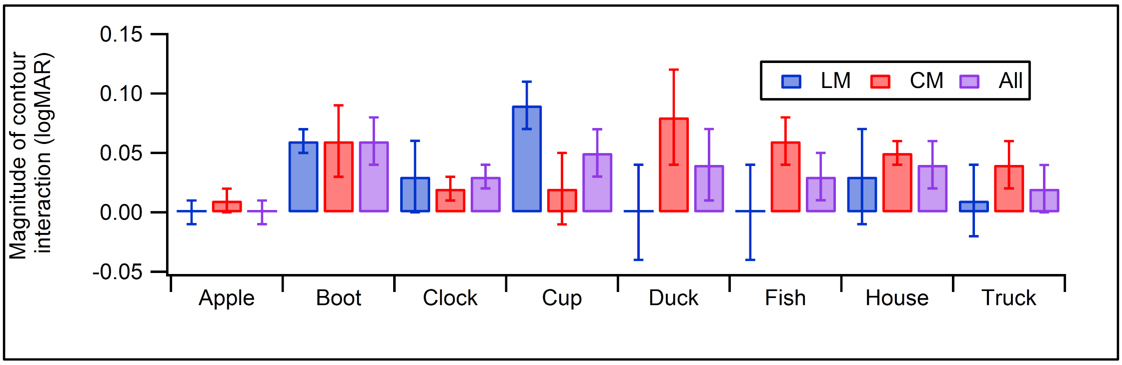


Figure 2.9: *Threshold Elevations for each of the Kay Picture optotypes averaged across all 4 participants (AM, IH, JEB, SL) for luminace-modulated ("LM"), contrast-modulated ("CM") and collapsed across stimulus conditions ("All"). The error bars indicate ±1SE.*

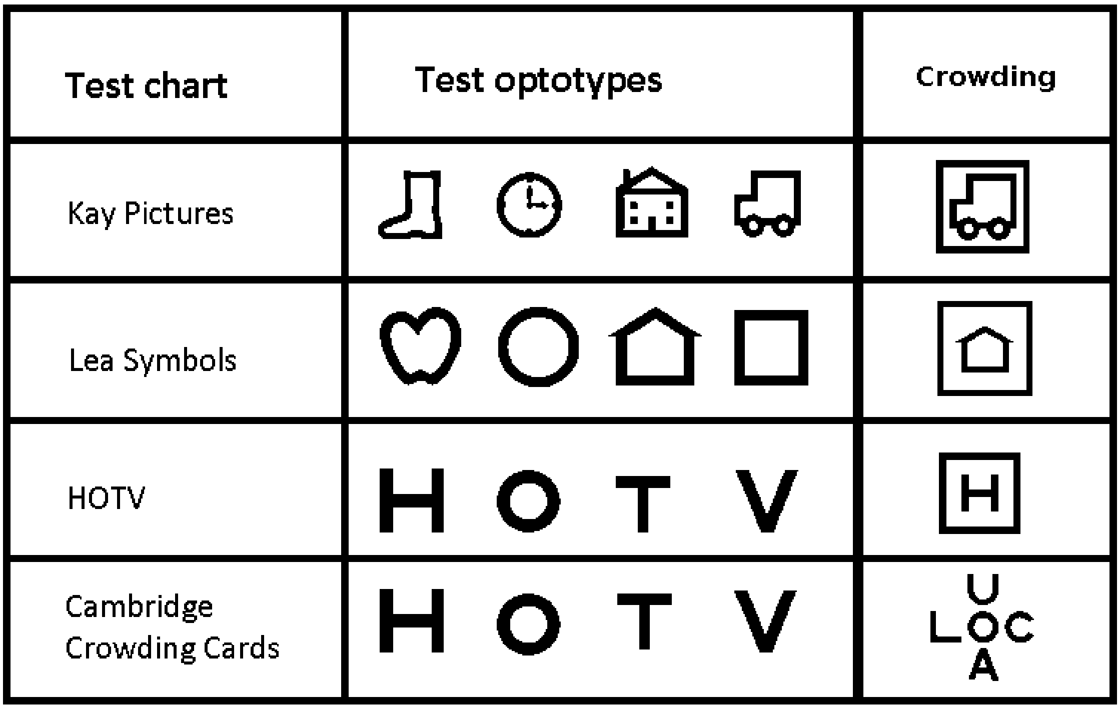


Figure 2.10: *The optotypes in the pre-literate visual acuity tests used, with an example of a crowded optotype for each test.*

Table 2.3: *An 8 (optotypes) × 3 (target-flanker separation) × 2 (stimulus condition) Repeated Measures ANOVA on data from the Kay Picture pilot experiment.*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
ANOVA Main Results						
Stimulus	**18**	**1.0**	**18**	**6900**	**<0.001**	**1**
Error	0.008	3.0	0.003			
Separation	**0.071**	**1.6**	**0.045**	**17**	**0.008**	**0.85**
Error	0.013	4.7	0.003			
Optotype	**0.44**	**2.7**	**0.16**	**7.0**	**0.013**	**0.70**
Error	0.19	8.2	0.023			
Stimulus*Separation	0.003	2.0	0.001	0.85	0.47	0.22
Error	0.009	6.0	0.001			
Stimulus*Optotype	**0.073**	**7.0**	**0.01**	**4.4**	**0.004**	**0.60**
Error	0.050	21	0.002			
Separation*Optotype	0.011	6.9	0.002	1.1	0.40	0.27
Error	0.030	21	0.001			
Stimulus*Sep*Optotype	0.018	14	0.001	1.0	0.43	0.26
Error	0.053	42	0.001			
Planned Comparisons of contour interaction with “isolated” optotypes:						
1 stroke width	**0.077**	**1**	**0.077**	**16.6**	**0.027**	
Error	0.014	3.0	0.005			
5 stroke widths	0.007	1.0	0.007	6.6	0.083	
Error	0.003	3.0	0.001			

In summary, visual acuity was highest (worst) when measured with the “apple” and lowest (best) when measured with the “duck”. The magnitude of contour interaction with a box 1 stroke width away was smallest with the “apple”. The “fish” and “cup” optotypes are not designed on a square grid like the other 6 optotypes; the “fish” being wider and the “cup” being taller. A square box would result in different separations between the optotype edges and the box vertically and horizontally. Keeping the separation constant would result in a rectangular box that could lead to a shape cue, which would help in the recognition of the optotype without being able to resolve the optotype.

The four optotypes deemed most appropriate to use in the following experiments were “boot”, “clock”, “house” and “truck”. The optotypes used for each of the tests are shown in Figure 2.10.

2.4.2 Pilot Experiment 2: Figure-ground configurations

There was very little difference in the magnitude of contour interaction between increment and decrement conditions for most target-flanker separations except when the box abutted the target optotype, as shown in Figure 2.11 (data are presented in two panels for ease of viewing, not necessarily for theoretical reasons). The difference in the magnitude of contour interaction when measured with a black optotype on a white background (Figure 2.11 left black filled symbols) compared to on a mean luminance background (Figure 2.11 right filled green symbols) was very small (mean 0.01 ± 0.02 logMAR difference, averaged across all separations) as was the difference in peak magnitude of contour interaction (mean 0.02 ± 0.02 logMAR). The addition of noise (L with mean luminance background vs LM seen in Figure 2.11 right) results in a slight reduction (mean 0.02 ± 0.01 logMAR, averaged across all separations) in the magnitude of contour interaction and a small reduction (mean 0.03 ± 0.01 logMAR) reduction in the peak magnitude of contour interaction. The results shown here indicate that the effect of using increment CM stimuli and decrement LM stimuli should have minimal influence on the measured magnitudes of contour interaction.

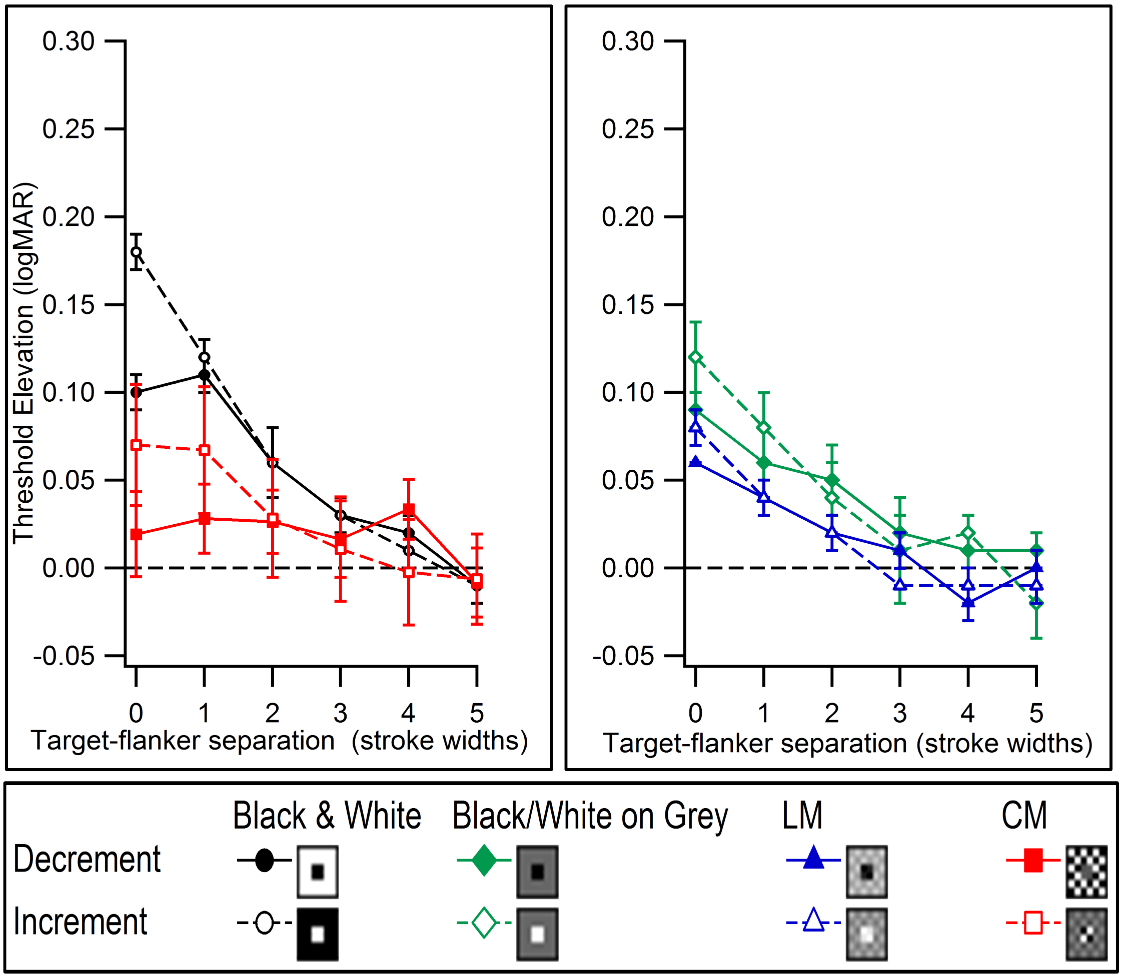


Figure 2.11: *Threshold Elevations for increment and decrement versions of each of the stimulus conditions and each of the tests. Error bars indicate* $\pm 1SE$.

In order to compare across L, LM and CM tests in Experiment 1, it is therefore suitable to use the "intuitive" figure-ground relationships for L, LM and CM tests. These are: black optotypes on a white background (L), decrement luminance-modulated noise optotype on a mean luminance noise background (LM) and an increment high contrast contrast-modulated noise optotype on a low contrast contrast-modulated background (CM). Figure 2.1 demonstrates that the increment version of the CM stimulus condition is more intuitive than the decrement version.

2.4.3 Main experiment

The results were analysed by directly comparing the standard luminance (L) and the luminance-modulated (LM) conditions, and separately comparing the luminance modulated (LM) and contrast-modulated (CM) conditions. The standard luminance (L) condition is similar to the standard clinical setup. The contrast modulated (CM) condition is a new type of stimulus and the luminance modulated (LM) condition is similar to the luminance-defined (L) condition but with the addition of dynamic noise. The effect of noise *per se* can be examined by comparing the data obtained for the L and LM conditions. Because the dynamic noise is equivalent in the LM and CM conditions, visual acuity and contour interaction/crowding effects for the new CM stimuli can be compared with LM stimuli, without specific noise effects. Contour interaction was investigated using the modified versions of the Kay Pictures, Lea Symbols and HOTV tests, each of which had a box surrounding a single optotype, except in the isolated condition where only a single optotype was shown. Contour-interaction and crowding were investigated by comparing the HOTV test and Cambridge Crowded test, both of which (after the exclusion of the "X" as previously described) had the HOTV target optotypes but with a surrounding box and flanking letters, respectively.

2.4.4 Visual acuity

Acuities for the 4 different tests (each now with only 4 optotypes) for each of the target-flanker separations, averaged across all 5 participants, are shown in Figure 2.12. Visual acuity for isolated optotypes (i.e. those measured without any crowding or contour interaction features) were 0.62±0.05 logMAR worse with contrast-modulated (CM) stimuli than with standard luminance (L) stimuli, and 0.55 ± 0.12 logMAR worse than with luminance-modulated (LM) stimuli. The right-most point on each graph below shows visual acuity for isolated optotypes. Visual acuities measured with isolated Lea Symbols and HOTV letters were similar (mean 0.03 ± 0.02 logMAR difference across all stimuli) but were consistently lowest (best) when measured with isolated Kay Pictures (mean 0.12 ± 0.04 logMAR lower) with a similar difference for L (0.17 ± 0.04 logMAR) and LM (0.15 ± 0.04 logMAR) but a smaller difference with CM stimuli (0.05 ± 0.05 logMAR). Visual acuities with measured with the commercial "crowded" versions were also similar between the Lea Symbols (-0.03 ± 0.02 logMAR) and HOTV (-0.07 ± 0.03 logMAR) tests (Anstice et al., 2017*b*). Anstice et al. (2017*b*) also obtained visual acuities that were 0.13 ± 0.04 logMAR lower (better) with the commercial "crowded" Kay Picture test than with the commercial "crowded" Lea Symbols and HOTV tests.

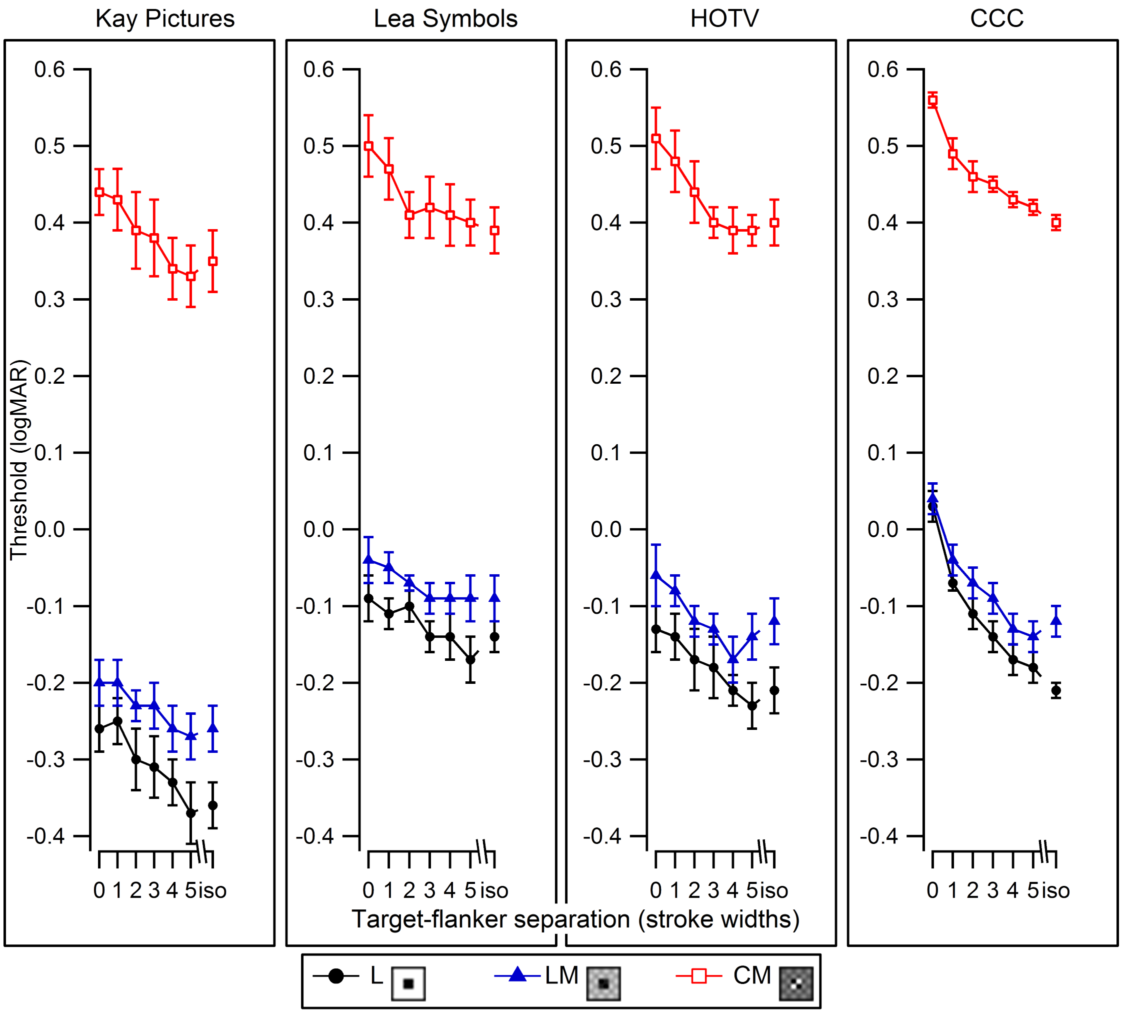


Figure 2.12: *Visual Acuity thresholds averaged across all five participants for standard luminance (L), luminance-modulated (LM) and contrast-modulated (CM) versions of all four tests: Kay Pictures, Lea Symbols, HOTV and Cambridge Crowded test (CCC). Error bars indicate* $\pm 1SE$.

Standard luminance (L) and luminance-modulated (LM) stimuli

A 2 (stimulus) $\times$ 4 (test) $\times$ 7 (target-flanker separation) repeated measures ANOVA (see Table 2.4) revealed that visual acuity measurements across all measured target-flanker separations (including without flankers) were significantly lower (better) [F(1.0,4.0)=40, p=0.003] with the L stimulus condition (mean -0.19 ± 0.11 logMAR) compared to the LM stimulus condition (mean -0.13±0.09 logMAR) regardless of the test as indicated by lack of a significant interaction between the test and stimulus conditions ($p > 0.05$). The Kay Picture test resulted in the lowest visual acuities (mean -0.27 ± 0.08 logMAR averaged across all participants, target-flanker separations and stimulus conditions) and highest with the Lea Symbols and Cambridge Crowding test (mean -0.10±0.06 logMAR and -0.10±0.08 logMAR respectively). Visual acuity measurements were statistically significantly different between tests [F(3,12)=34, $p < 0.001$]. A Tukey HSD pairwise comparison showed that the Kay Picture test resulted in significantly lower visual acuity measurements than with the Lea Symbols (p=0.006) and Cambridge Crowding test (p=0.01). The target-flanker separation had a significant effect on visual acuity measurements [F6,24)=96, $p< 0.001$]. This is investigated later on during the investigation of contour-interaction and crowding.

Table 2.4: *A Repeated Measures ANOVA for 2 stimulus conditions (L and LM), 4 tests (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding test) and 7 target-flanker separations (isolated, 0-5 stroke widths) for 5 participants.*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	**1.4**	**3**	**0.48**	**41**	**<0.001**	**0.91**
Error	0.14	12	0.012			
Stimulus	**0.25**	**1**	**0.25**	**40**	**0.003**	**0.91**
Error	0.025	4	0.006			
Separation	**0.40**	**4.4**	**0.090**	**96**	**<0.001**	**0.96**
Error	0.016	18	0.001			
Test*Stimulus	0.011	3	0.004	1.7	0.22	0.30
Error	0.025	12	0.002			
Test*Sep	**0.10**	**4.8**	**0.021**	**8.4**	**<0.001**	**0.68**
Error	0.048	19	0.002			
Stimulus*Sep	**0.019**	**5.0**	**0.004**	**5.6**	**0.002**	**0.58**
Error	0.014	20	0.001			
Test*Stimulus*Sep	0.011	18	0.001	1.4	0.17	0.26
Error	0.032	72	0.000			

Luminance-modulated (LM) and contrast-modulated (CM) stimuli

A 2 (stimulus) × 4 (test) × 7 (target-flanker separation) repeated measures ANOVA (see Table 2.5) revealed significantly lower visual acuities [F(1,4)=3023, $p< 0.001$] with the LM stimuli than with the CM stimuli (mean -0.13 ± 0.09 logMAR and 0.42 ± 0.08 logMAR respectively, averaged across all participants, target-flanker separations and tests). Visual acuity measurements were significantly different between tests [F(3,12)=16, $p< 0.001$] but there was a significant interaction between test and stimulus condition. LM visual acuities (see Table 2.6) were significantly different among tests [$F(1.9,7.7)=31$, $p< 0.001$] with significantly lower visual acuities obtained with the Kay Picture test than the Lea Symbols test ($p=0.006$) and the Cambridge Crowding test ($p=0.013$) but visual acuities were not significantly different among CM tests ($p> 0.05$), see Table 2.7. Target-flanker separation had a significant effect on visual acuity measurements [$F(4.4,18)=73$, $p< 0.001$]. This is investigated later on during the investigation of contour-interaction and crowding.

Table 2.5: *A Repeated Measures ANOVA for 2 stimulus conditions (LM and CM), 4 tests (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding test) and 7 target-flanker separations (isolated, 0-5 stroke widths) for 5 participants.*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	**0.62**	**3**	**0.21**	**16**	**<0.001**	**0.80**
Error	0.16	12	0.013			
Stimulus	**21**	**1**	**21**	**3023**	**<0.001**	**1.0**
Error	0.028	4	0.007			
Separation	**0.39**	**4.4**	**0.088**	**73**	**<0.001**	**0.95**
Error	0.021	18	0.001			
Test*Stimulus	**0.11**	**2.2**	**0.051**	**6.9**	**0.014**	**0.63**
Error	0.065	8.9	0.007			
Test*Sep	**0.044**	**16**	**0.003**	**3.8**	**<0.001**	**0.49**
Error	0.046	63	0.001			
Stimulus*Sep	**0.011**	**4.1**	**0.003**	**3.1**	**0.042**	**0.44**
Error	0.014	17	0.001			
Test*Stimulus*Sep	0.012	7.7	0.002	1.1	0.37	0.22
Error	0.041	31	0.001			

Table 2.6: *A Repeated Measures ANOVA for LM versions of 4 tests (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding test) and 7 target-flanker separations (isolated, 0-5 stroke widths) for 5 participants.*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	**0.61**	**1.9**	**0.32**	**31**	**<0.001**	**0.89**
Error	0.78	7.7	0.010			
Separation	**0.15**	**6.0**	**0.025**	**41**	**<0.001**	**0.91**
Error	0.051	24	0.001			
Test*Sep	**0.034**	**7.2**	**0.005**	**4.7**	**0.001**	**0.54**
Error	0.031	29	0.001			

Table 2.7: *A Repeated Measures ANOVA for CM versions of 4 tests (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding test) and 7 target-flanker separations (isolated, 0-5 stroke widths) for 5 participants.*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	0.12	2.6	0.045	3.4	0.065	0.46
Error	0.14	11	0.013			
Separation	**0.25**	**6.0**	**0.042**	**50**	**<0.001**	**0.93**
Error	0.020	24	0.001			
Test*Separation	0.018	18	0.001	1.3	0.20	0.25
Error	0.055	72	0.001			

2.4.5 Magnitude of contour interaction

The magnitude of contour interaction, i.e. the difference between flanked and isolated visual acuity as a function of separation between the flankers and the optotype, is shown for L and LM stimulus conditions in Figures 2.15 and 2.16, and for LM and CM stimulus conditions in Figures 2.17 and 2.18, which is discussed below. Peak magnitude of contour interaction is the largest difference found between isolated and flanked acuities (Levi, Hariharan and Klein, 2002; Hariharan et al., 2005; Levi, 2005; Chung et al., 2007, 2008*b*; Hairol et al., 2013). For individual observers, the peak magnitude of contour interaction occurred when the target was either abutting or 1 stroke-width away from the optotype (see Figure 2.13). Clinically, having abutting contours would not be appropriate as the surrouding contours would not be resolvable from the target optotype. The magnitude of contour interaction at 1 stroke width target-flanker separation is shown in Figure 2.14 in addition to the peak magnitude of contour interaction.

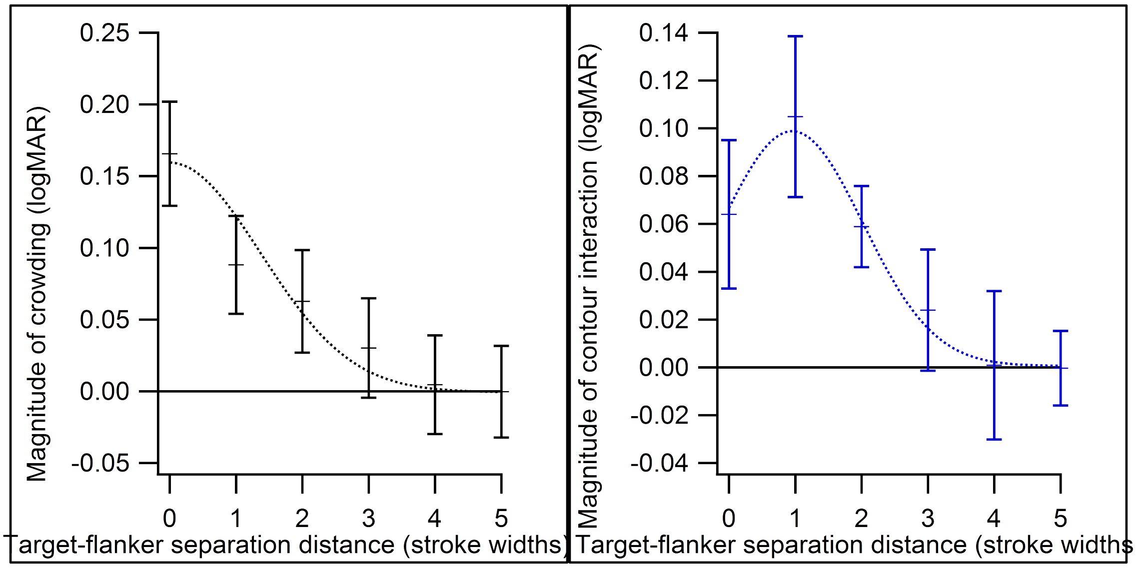


Figure 2.13: *Examples of the magnitude of contour-interaction and crowding plotted against target-flanker separation distance, showing the peak at abutting (left) and at 1 stroke width (right). Gaussians are fitted to the data points. Error bars indicate* $\pm 1SD$.

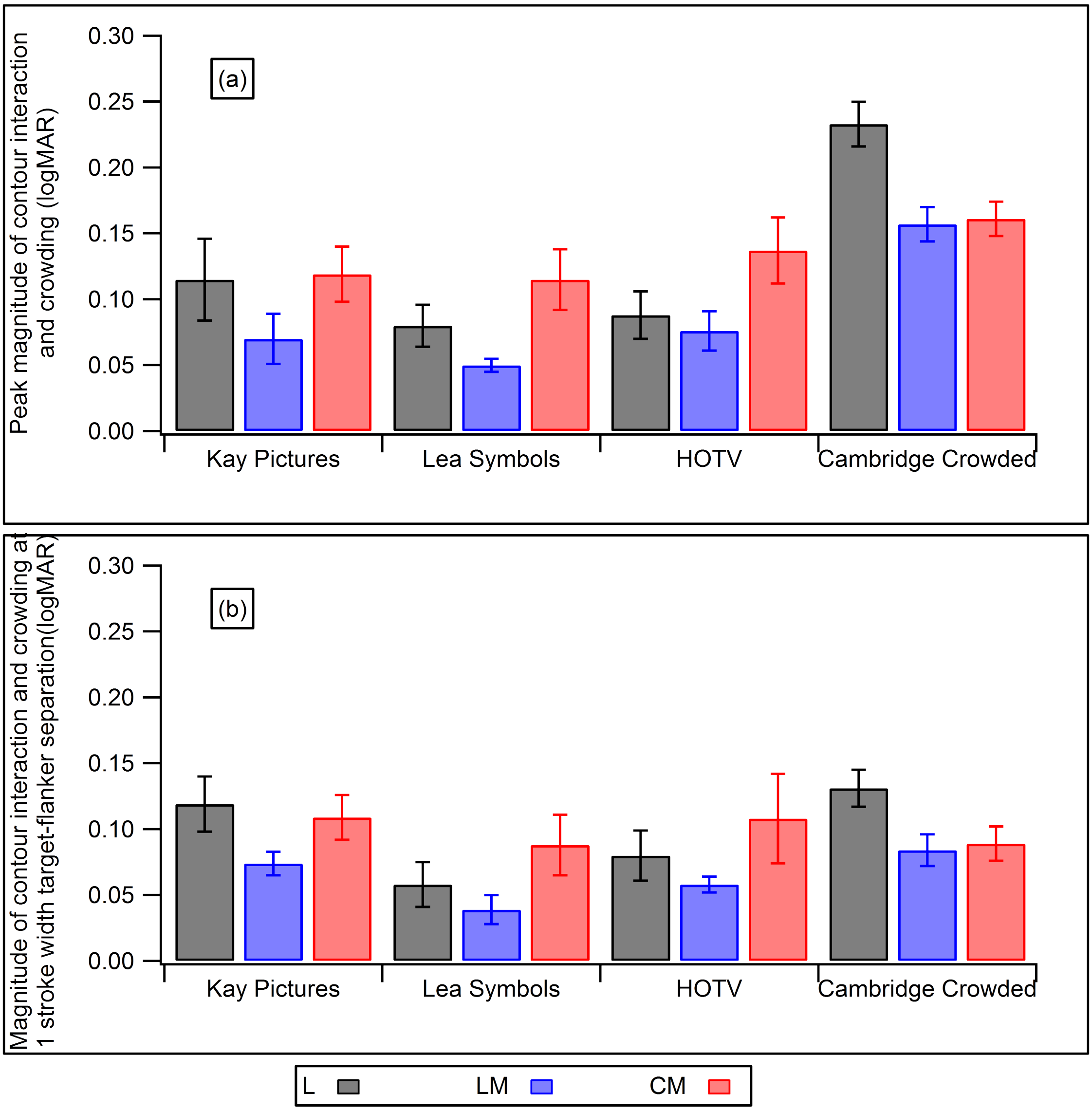


Figure 2.14: *The peak magnitude of contour interaction/crowding (a) and the magnitude of contour interaction/crowding at 1 stroke width target-flanker separation (b) averaged across all 5 participants for all 4 tests. Error bars indicate* $\pm 1SE$.

Standard luminance (L) and luminance-modulated (LM) stimuli

The magnitude of contour interaction, as shown in Figure 2.15, was similar across tests. Noise appears to reduce the effects of contour interaction (see Figure 2.16) and as such the magnitude of contour interaction was larger with L than LM stimuli. A 2 (stimulus) $\times$ 3 (test) $\times$ 6 (target-flanker separation) repeated measures ANOVA (see Table 2.9) revealed that this difference was statistically significant [F(1.0,4.0)=11, p=0.028]. Peak magnitude of contour interaction was consistently larger for L than LM stimuli (see Figure 2.14) a 2 (stimulus) $\times$ 3 (test) repeated measures ANOVA (see Table 2.8) but this difference did not reach statistical significance. The magnitude of contour interaction at 1 stroke width target-flanker separation was also consistently larger for L than LM stimuli (see Figure 2.14). As shown in Figures 2.15 and 2.16, the magnitude of contour interaction reduced as the target-flanker separation increased, with a significant difference in the magnitude of contour interaction across target-flanker separations [$F(3.0,12)=67$, $p< 0.001$].

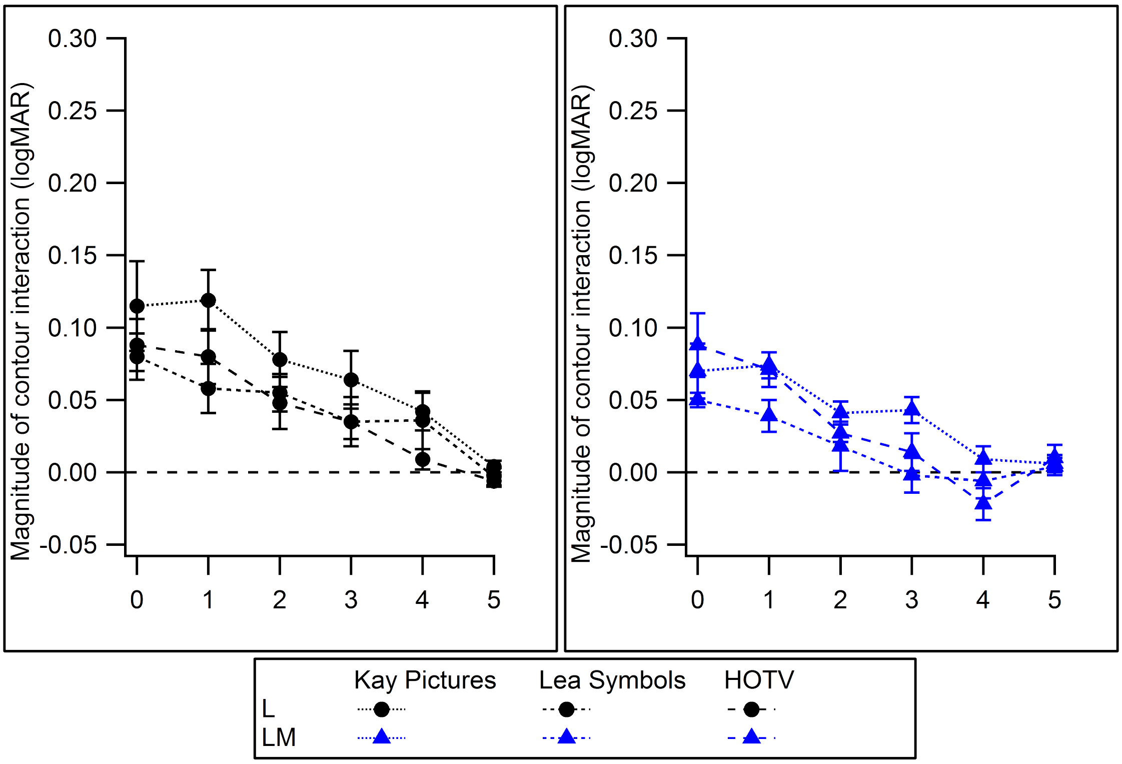


Figure 2.15: *Magnitude of contour interaction across target-flanker separations (0-5 stroke widths) for standard luminance (L) and luminance-modulated (LM) versions of the Kay Pictures, Lea Symbols and HOTV tests averaged across all participants. Error bars indicate ±1SE.*

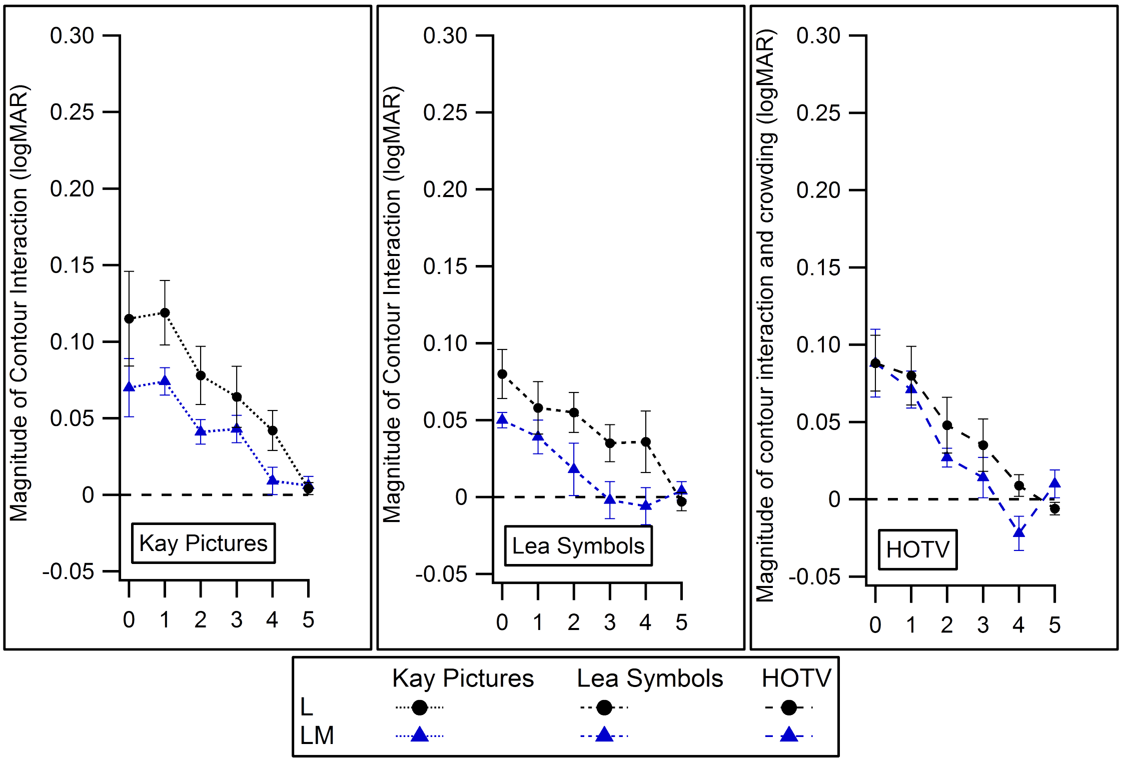


Figure 2.16: *Magnitude of contour interaction across target-flanker separations (0-5 stroke widths) for standard luminance (L) and luminance-modulated (LM) versions of the Kay Pictures, Lea Symbols and HOTV tests averaged across all participants. Error bars indicate ±1SE.*

Table 2.8: *Repeated measures ANOVA for the maximum magnitude of contour interaction with 2 stimulus conditions (L and LM) and 3 tests (Kay Pictures, Lea Symbols and HOTV).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	0.008	1.3	0.006	1.7	0.26	0.29
Error	0.018	5.4	0.003			
Stimulus	0.005	1.0	0.005	4.0	0.12	0.50
Error	0.005	4.0	0.001			
Test*Stimulus	0.002	2.0	0.001	1.7	0.24	0.30
Error	0.004	8.0	0.001			

Table 2.9: *Repeated measures ANOVA with 2 stimulus conditions (L and LM), 3 tests (Kay Pictures, Lea Symbols and HOTV) and 6 target-flanker separations (0-5 stroke widths).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	0.19	1.5	0.012	1.9	0.23	0.32
Error	0.040	6.0	0.007			
Stimulus	**0.022**	**1.0**	**0.022**	**11**	**0.028**	**0.74**
Error	0.008	4.0	0.002			
Separation	**0.16**	**3.0**	**0.051**	**67**	**$<$0.001**	**0.94**
Error	0.009	12	0.001			
Test*Stimulus	0.003	2.0	0.001	0.73	0.51	0.15
Error	0.016	8.0	0.002			
Test*Separation	0.012	5.1	0.002	1.5	0.23	0.27
Error	0.031	8.9	0.003			
Stimulus*Separation	0.009	5.0	0.002	2.3	0.089	0.36
Error	0.015	20	0.001			
Test*Stimulus*Sep	0.003	10	0.000	0.73	0.69	0.15
Error	0.017	40	0.000			

Luminance-modulated (LM) and contrast-modulated (CM)

The magnitude of contour interaction, as shown in Figure 2.17, was similar across test. As shown in Figure 2.18, contour interaction effects appear to be stronger with CM than for LM stimuli with a larger magnitude of contour interaction across all separations for CM than LM stimuli. A 2 (stimulus) $\times$ 3 (test) $\times$ 6 (target-flanker separation) repeated measures ANOVA (see Table 2.11) revealed that this difference was statistically significant [F(1.0,4.0)=8.4, p=0.045]. The peak magnitude of contour interaction was also consistently larger with CM than LM stimuli (see Figure 2.14) and a 2 (stimulus) $\times$ 3 (test) repeated measures ANOVA (see Table 2.10) revealed that this difference was significant [F(1.0,4.0)=68, p=0.001]. The magnitude of contour interaction at 1 stroke width target-flanker separation (see Figure 2.14) was also consistently larger for CM than LM stimuli. The magnitude of contour interaction reduced as the target-flanker separation increased, as shown in Figures 2.17 and 2.18 [$F(5.0,20)=110$, $p < 0.001$].

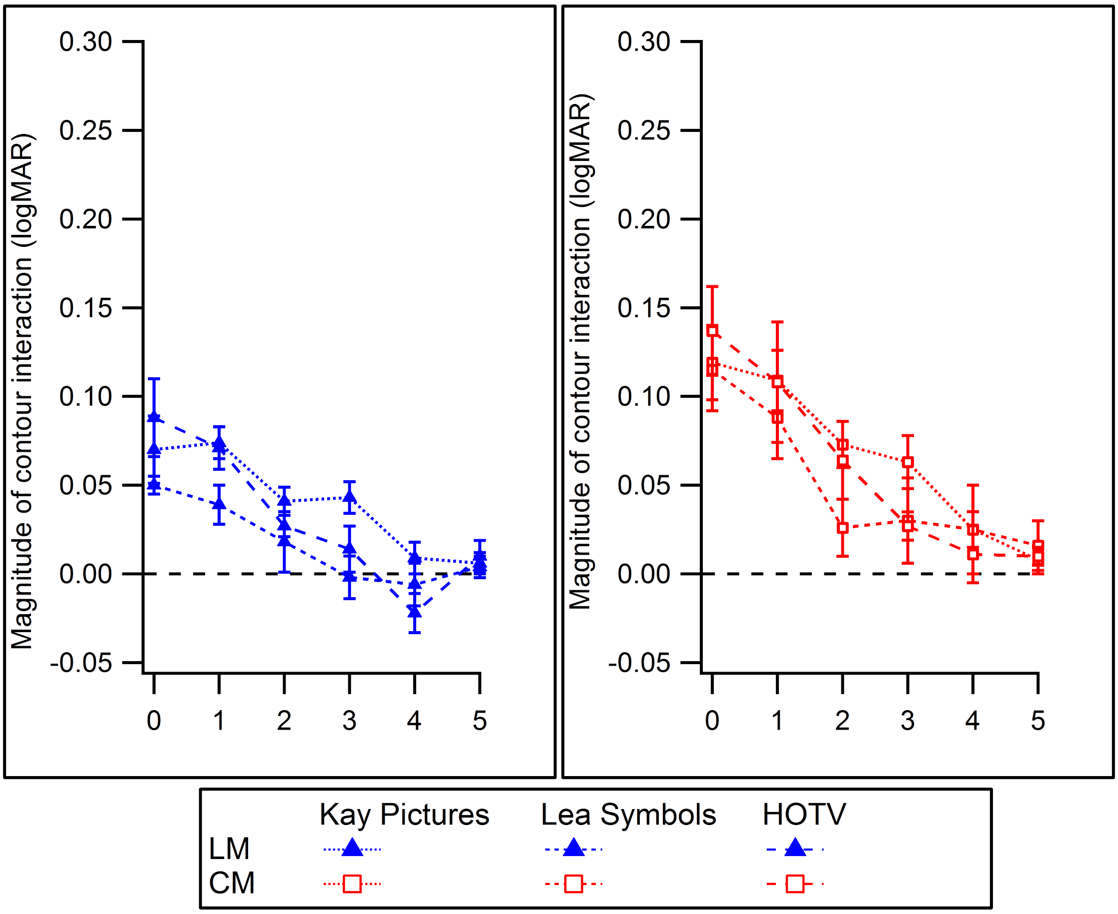


Figure 2.17: *Magnitude of contour interaction across target-flanker separations (0-5 stroke widths) for luminance-modulated (LM) and contrast-modulated (CM) versions of the Kay Pictures, Lea Symbols and HOTV tests averaged across all participants. Error bars indicate* $\pm 1SE$.

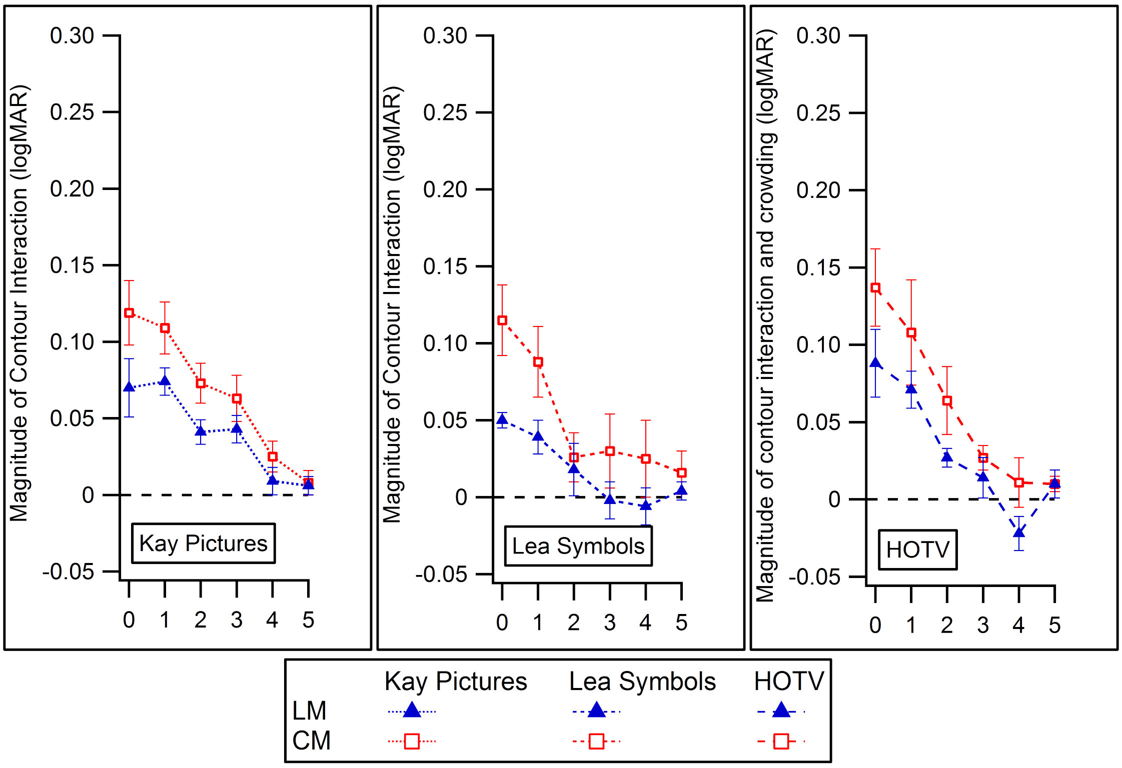


Figure 2.18: *Magnitude of contour interaction across target-flanker separations (0-5 stroke widths) for luminance-modulated (LM) and contrast-modulated (CM) versions of the Kay Pictures, Lea Symbols and HOTV tests averaged across all participants. Error bars indicate* $\pm 1SE$.

Table 2.10: *Repeated measures ANOVA for the maximum magnitude of contour interaction with 2 stimulus conditions (LM and CM) and 3 tests (Kay Pictures, Lea Symbols and HOTV).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	0.007	2.0	0.004	1.8	0.23	0.31
Error	0.017	8.0	0.002			
Stimulus	**0.024**	**1.0**	**0.024**	**68**	**0.001**	**0.94**
Error	0.001	4.0	0.000			
Test*Stimulus	0.000	1.2	0.000	0.033	0.90	0.008
Error	0.018	4.7	0.004			

Table 2.11: *Repeated measures ANOVA with 2 stimulus conditions (LM and CM), 3 tests (Kay Pictures, Lea Symbols and HOTV) and 6 target-flanker separations (0-5 stroke widths).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	0.011	1.7	0.007	1.1	0.38	0.21
Error	0.042	6.6	0.006			
Stimulus	**0.037**	**1.0**	**0.037**	**8.4**	**0.045**	**0.68**
Error	0.018	4.0	0.004			
Separation	**0.21**	**5.0**	**0.042**	**110**	**$<$0.001**	**0.96**
Error	0.008	20	0.000			
Test*Stimulus	0.000	1.7	0.000	0.034	0.95	0.008
Error	0.034	7.0	0.005			
Test*Separation	0.015	7.8	0.002	2.1	0.069	0.34
Error	0.029	31	0.001			
Stimulus*Separation	0.010	3.0	0.003	3.3	0.058	0.45
Error	0.012	12	0.001			
Test*Stimulus*Sep	0.002	6.3	0.000	0.43	0.86	0.096
Error	0.023	25	0.001			

2.4.6 The magnitude of crowding compared to the magnitude of contour interaction

It has been suggested that flankers that are more similar to the target are likely to produce a larger detrimental effect on acuity than flanking contours (Kooi et al., 1994; Formankiewicz and Waugh, 2013; Song et al., 2014) but this has not previously been tested using LM and CM stimuli. In this section the magnitude of contour interaction and crowding are directly compared using the HOTV target optotypes with a surrounding box (for contour interaction) and with flanking letters (for crowding).

Standard luminance (L) and luminance-modulated (LM)

The magnitude of contour interaction was consistently smaller than the magnitude of crowding, as shown in Figure 2.19. A 2 (stimulus) $\times$ 2 (test) $\times$ 6 (target-flanker separations) repeated measures ANOVA (see Table 2.13) revealed that this difference was statistically significant [$F(1.0,4.0)=140$, $p< 0.001$]. The magnitude of contour interaction and crowding (see Figure 2.20) were significantly smaller with LM than L stimuli [$F(1.0,4.0)=9.4$, $p=0.037$]. The peak magnitude of contour interaction/crowding was consistently smaller with LM than L stimuli (see Figure 2.20) but this did not reach statistical significance (see Table 2.12). The magnitude of contour interaction and crowding reduced as the target-flanker separation increased and was significantly affected by the target-flanker separation [$F(2.6,11)=128$, $p< 0.001$] and this was significantly different for contour interaction and crowding [$F(2.7,11)=130$, $p< 0.001$].

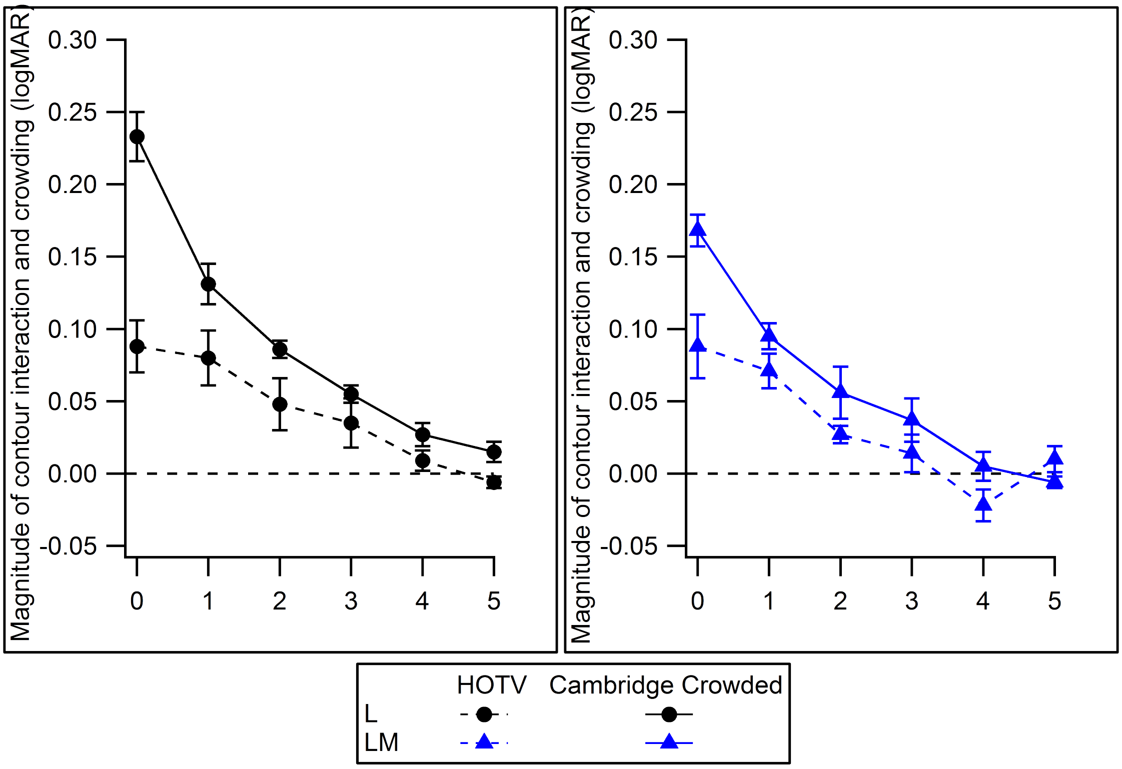


Figure 2.19: *Threshold Elevations for standard luminance (L) and luminance-modulated (LM) versions of the HOTV (which has a surrounding box) and Cambridge Crowding test (which has flanking letters) tests averaged across all participants. Error bars indicate $\pm 1SE$.*

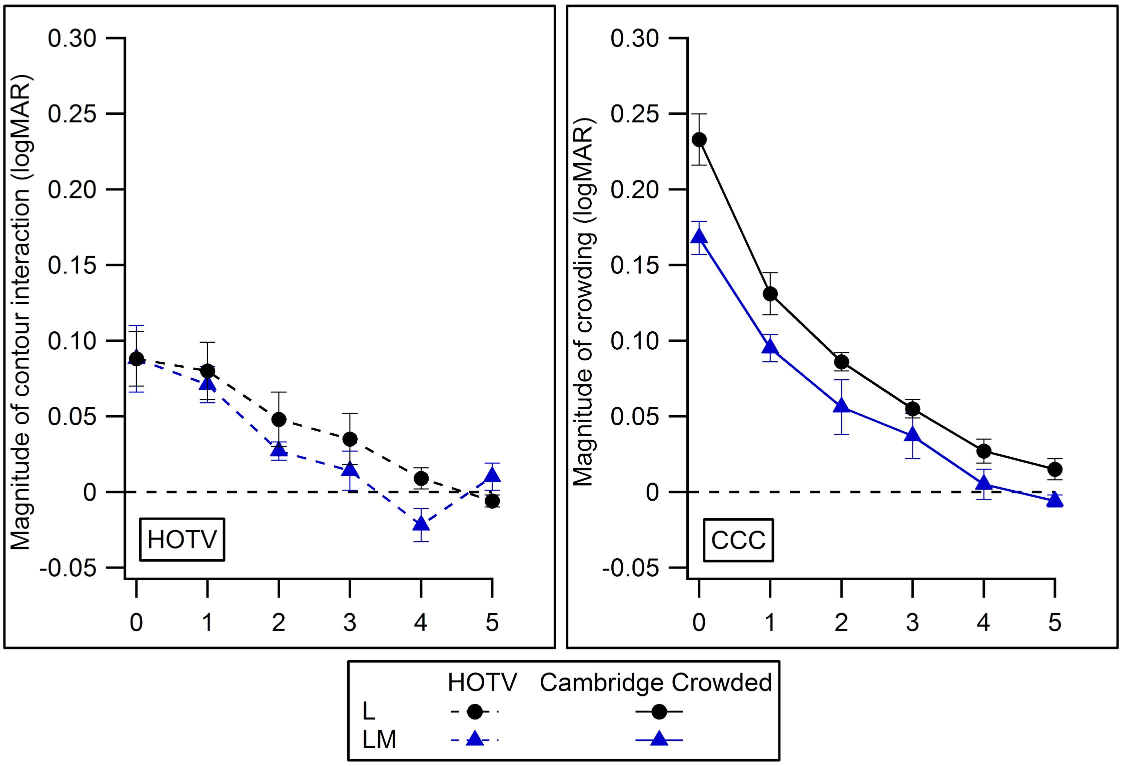


Figure 2.20: *Threshold Elevations for standard luminance (L) and luminance-modulated (LM) versions of the HOTV (which has a surrounding box) and Cambridge Crowding test (which has flanking letters) tests averaged across all participants. Error bars indicate ±1SE.*

Table 2.12: *Repeated measures ANOVA for the maximum magnitude of contour interaction (HOTV test) and crowding (Cambridge Crowding test test) with 2 stimulus conditions (L and LM).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	**0.057**	**1.0**	**0.057**	**188**	**<0.001**	**0.98**
Error	0.001	4.0	0.000			
Stimulus	0.006	1.0	0.006	3.2	0.15	0.45
Error	0.007	4.0	0.002			
Test*Stimulus	0.005	1.0	0.005	3.3	0.14	0.45
Error	0.006	4.0	0.001			

Table 2.13: *Repeated measures ANOVA with 2 stimulus conditions (L and LM), 2 tests (HOTV and Cambridge Crowding test) and 6 target-flanker separations (0-5 stroke widths).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	**0.059**	**1.0**	**0.059**	**140**	**<0.001**	**0.97**
Error	0.002	4.0	0.000			
Stimulus	**0.021**	**1.0**	**0.021**	**9.4**	**0.037**	**0.70**
Error	0.009	4.0	0.002			
Separation	**0.31**	**2.7**	**0.11**	**130**	**<0.001**	**0.97**
Error	0.010	11	0.001			
Test*Stimulus	0.000	1.0	0.000	0.048	0.84	0.012
Error	0.012	4.0	0.003			
Test*Separation	**0.035**	**2.9**	**0.012**	**18**	**<0.001**	**0.82**
Error	0.008	12	0.001			
Stimulus*Separation	0.002	3.8	0.001	0.76	0.56	0.16
Error	0.013	15	0.001			
Test*Stimulus*Sep	0.005	2.9	0.002	3.2	0.063	0.45
Error	0.007	12	0.001			

Luminance-modulated (LM) and contrast-modulated (CM)

The magnitude of contour interaction and crowding were largest when the target and flankers were abutting and reduced as the target-flanker separation increased, as shown in Figure 2.21. A 2 (stimulus) $\times$ 2 (test) $\times$ 6 (separation) repeated measures ANOVA (see Table 2.15) revealed that the magnitude of contour interaction and crowding were significantly affected by the target-flanker separation [$F(3.6,15)=84$, $p< 0.001$]. Like with L and LM stimuli, there was a significant interaction between test and target-flanker separation [$F(5.0,20)=3.5$, $p=0.020$] but there was no significant difference between contour interaction and crowding. Figure 2.22 suggests that there is a significant difference between contour interaction and crowding with LM but not CM stimuli. To investigate this a 2 (test) $\times$ 6 (separation) repeated measures ANOVA was done for LM (see Table 2.16) and CM (see Table 2.17) stimuli separately which revealed a significant difference between contour interaction and crowding with LM stimuli [F(1.0,4.0)=17, p=0.014] but not with CM stimuli [F(1.0,4.0)=0.064, p=0.81]. The peak magnitude of contour interaction is significantly larger for CM than LM stimuli [F(1.0,4.0)=8.3, p=0.045] but, as can be seen in Figure 2.14, although the magnitude of contour interaction is greater with CM than LM stimuli at the peak and at 1 stroke width separation, the magnitude of crowding is similar (see Table 2.14).

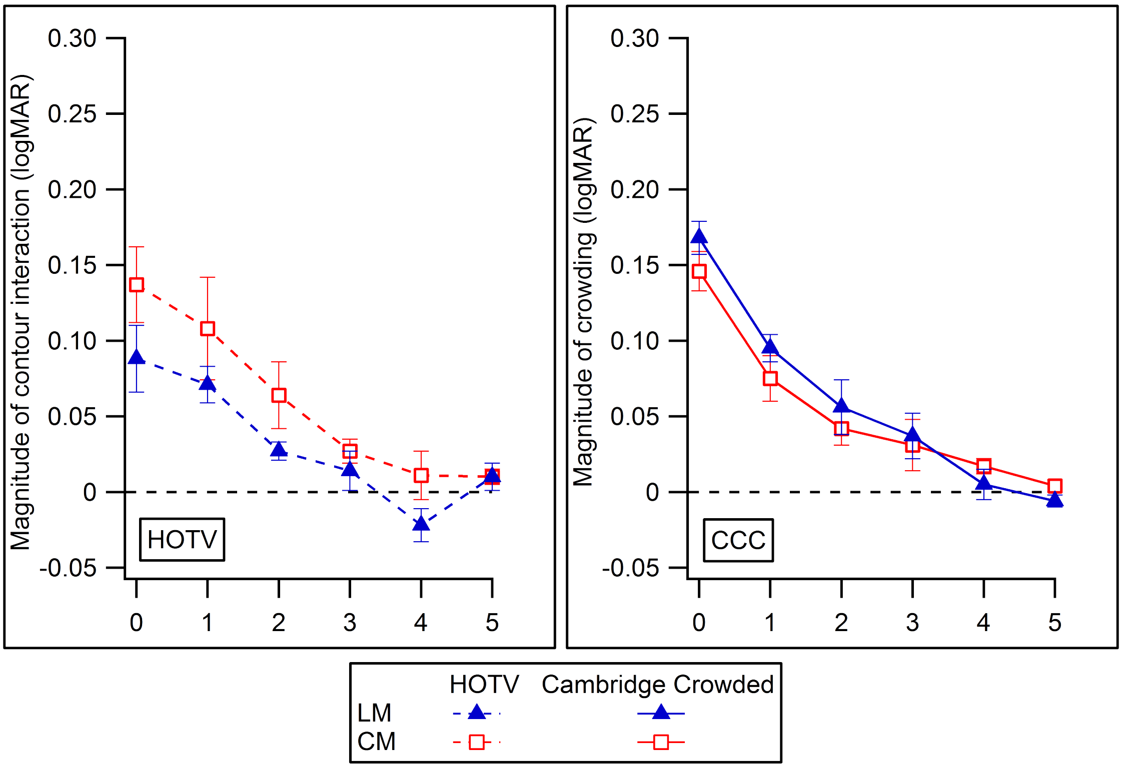


Figure 2.21: *Threshold Elevations for luminance-modulated (LM) and contrast-modulated (CM) versions of the HOTV (which has a surrounding box) and Cambridge Crowding test (which has flanking letters) tests averaged across all participants. Error bars indicate $\pm 1SE$.*

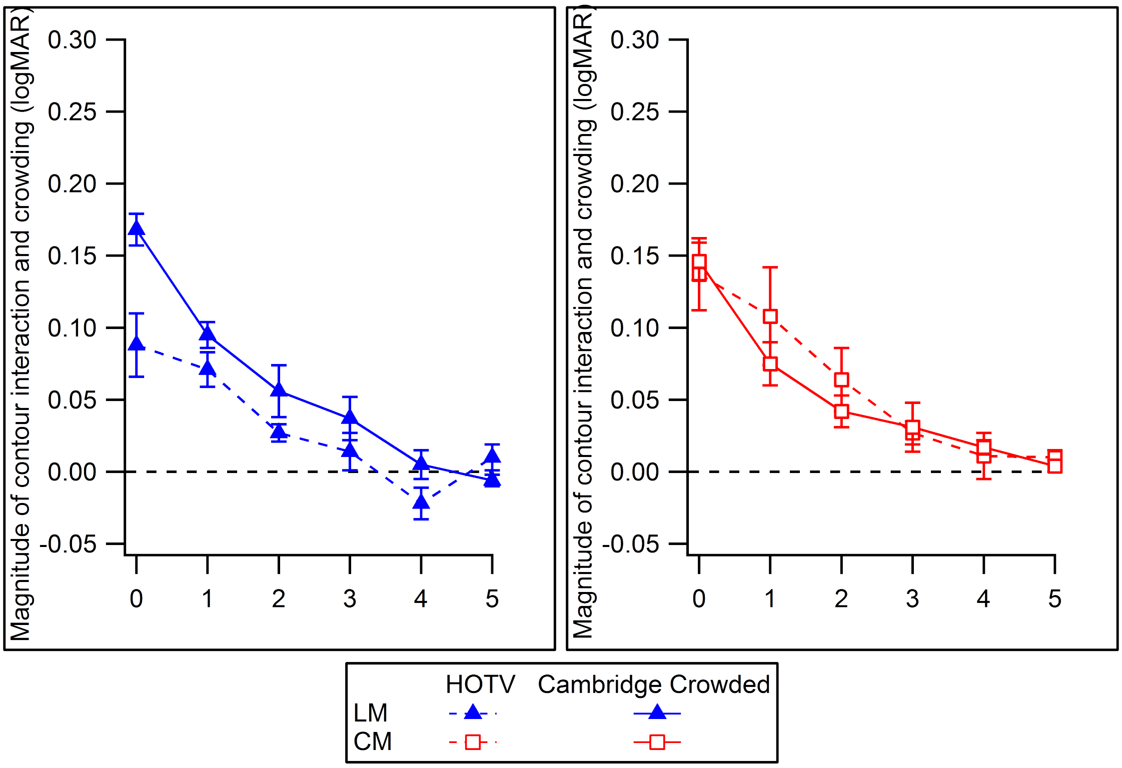


Figure 2.22: *Threshold Elevations for luminance-modulated (LM) and contrast-modulated (CM) versions of the HOTV (which has a surrounding box) and Cambridge Crowding test (which has flanking letters) tests averaged across all participants. Error bars indicate* $\pm 1SE$*.*

Table 2.14: *Repeated measures ANOVA for the maximum magnitude of contour interaction (HOTV test) and crowding (Cambridge Crowding test) with 2 stimulus conditions (LM and CM).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	**0.011**	**1.0**	**0.011**	**8.3**	**0.045**	**0.68**
Error	0.005	4.0	0.001			
Stimulus	0.004	1.0	0.004	2.0	0.23	0.34
Error	0.007	4.0	0.002			
Test*Stimulus	0.004	1.0	0.004	2.4	0.19	0.38
Error	0.007	4.0	0.002			

Table 2.15: *Repeated measures ANOVA with 2 stimulus conditions (LM and CM), 2 tests (HOTV and Cambridge Crowding test) and 6 target-flanker separations (0-5 stroke widths).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	0.011	1.0	0.011	4.2	0.11	0.51
Error	0.010	4.0	0.003			
Stimulus	0.009	1.0	0.009	1.6	0.28	0.28
Error	0.023	4.0	0.006			
Separation	**0.27**	**3.6**	**0.073**	**84**	$<$**0.001**	**0.95**
Error	0.013	15	0.001			
Test*Stimulus	0.016	1.0	0.016	4.8	0.094	0.55
Error	0.014	4.0	0.003			
Test*Separation	**0.009**	**5.0**	**0.002**	**3.5**	**0.020**	**0.47**
Error	0.011	20	0.001			
Stimulus*Separation	0.001	5.0	0.000	0.28	0.92	0.064
Error	0.015	20	0.001			
Test*Stimulus*Sep	0.006	5.0	0.001	2.1	0.11	0.34
Error	0.011	20	0.001			

Table 2.16: *Repeated measures ANOVA for the magnitude of contour interaction (HOTV test) and crowding (Cambridge Crowding test) with LM stimuli across all target-flanker separations (0-5 stroke widths).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	**0.027**	**1.0**	**0.027**	**17**	**0.014**	**0.81**
Error	0.006	4.0	0.002			
Separation	**0.14**	**5.0**	**0.027**	**56**	**<0.001**	**0.93**
Error	0.010	20	0.000			
Test*Separation	**0.011**	**2.4**	**0.004**	**5.2**	**0.025**	**0.57**
Error	0.008	9.8	0.001			

Table 2.17: *Repeated measures ANOVA for the magnitude of contour interaction (HOTV test) and crowding (Cambridge Crowding test) with CM stimuli across target-flanker separations (0-5 stroke widths).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	0.000	1.0	0.000	0.064	0.81	0.016
Error	0.018	4.0	0.004			
Separation	**0.13**	**3.7**	**0.036**	**29**	**<0.001**	**0.88**
Error	0.018	15	0.001			
Test*Separation	0.004	5.0	0.001	1.3	0.31	0.24
Error	0.013	20	0.001			

2.4.7 Extent of contour interaction/crowding

To objectively determine the extent of contour interaction and crowding using Gaussian fits, all data are fit with a Gaussian function (as shown in Figure 2.23) in the form:

$$F(sep) = A \times exp(-(sep^2/2\sigma^2)) \tag{2.3}$$

where sep is the target-flanker separation distance, A is the peak amplitude of the threshold elevation, and σ is the standard deviation of the Gaussian. The extent of contour interaction is defined as two standard deviations of the Gaussian fit to the data.

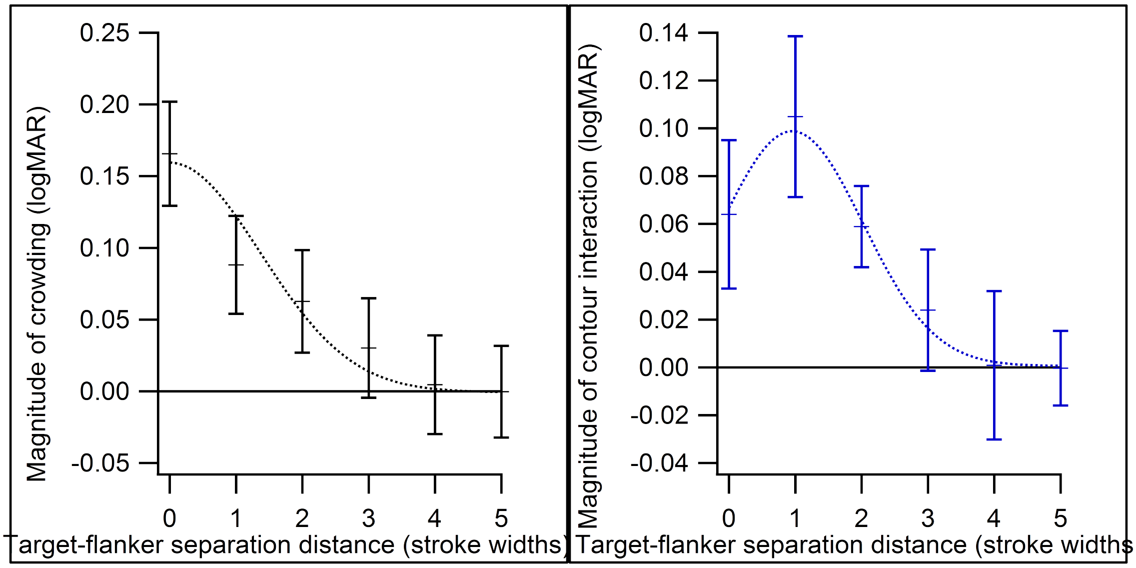


Figure 2.23: *Examples of Gaussian functions fit to crowding (left) and contour interaction (right) data.*

The extent of contour interaction and crowding (also known as "critical spacing", for example by: Pelli, Palomares and Majaj, 2004) was defined in two ways: (1) twice the standard deviation of a Gaussian function fit to the threshold elevation data (Chung et al., 2001; Levi, Klein and Hariharan, 2002; Felisberti et al., 2005; Hariharan et al., 2005; Chung et al., 2007, 2008*a*; Mareschal et al., 2010), and (2) the closest target-flanker separation at which flanked acuity was not significantly different from isolated acuity using post hoc Tukey HSD comparisons (Danilova and Bondarko, 2007; Croates et al., 2013; Hairol et al., 2013). Due to a lack of strong consensus in the literature, both methods were used. As well as using our standard units of stroke-widths, spatial extent was also assessed in units of optotype width and minutes of arc. Because of the different numbers of stroke-widths per optotype size for each test, estimates of extent will vary across test.

The extent of contour interaction was measured so that:

1. the target-flanker distance within which contour interaction and crowding occur could be compared to the current commercial placement for visual acuity tests.

2. for the next experiment with normal children (Experiment 2) the flankers are placed within the region in which contour interaction and crowding occurs.

In order to determine which units of separation are most consistent across test, the measured extent of contour interaction and crowding was analysed using units of stroke width, optotype width and minutes of arc. The average visual acuity for all normal adult participants for all 3 stimulus conditions without flankers was used for calculating the extent of contour interaction and crowding in minutes of arc.

Extent of contour-interaction/crowding measured with Gaussian fits

The variance in the extent of contour interaction and crowding (determined using a Gaussian fit) across all stimulus conditions (L, LM and CM) and tests (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding test was investigated to ensure the best units for defining the position of the flankers (see Table 2.18). The variance was smallest with stroke widths for L and LM stimuli and the average variance across stimulus conditions was smallest for stroke widths (25%). The total variance in extent of contour interaction/crowding was smallest with stroke widths (16%). In order to determine a single placement for the flankers for Experiment 2 (using normal children), it is necessary to determine which units (stroke widths, optotype widths or minutes of arc) is most consistent across tests and stimulus conditions. For this purpose, the magnitude of contour interaction/crowding are checked for significant effects of stimulus condition or test to ensure the placement of flankers chosen is suitable across all stimuli and tests.

Table 2.18: *The average extent of contour interaction and crowding measured using a Gaussian fit ±1SE and the variance (SE/average) of contour interaction and crowding across stimulus conditions and tests for stroke widths, optotype widths and minutes of arc.*

	Stroke widths	**Optotype widths**	**Arcmin**
Standard luminance (L)	2.5 ± 0.6 26%	0.40 ± 0.14 34%	1.6 ± 0.5 29%
Luminance modulated (LM)	1.3 ± 0.3 20%	0.21 ± 0.07 32%	0.91 ± 0.20 22%
Contrast modulated (CM)	2.0 ± 0.6 29%	0.31 ± 0.10 33%	4.9 ± 1.4 27%
Average	25%	33%	27%
Total variance across all stimulus conditions	1.9 ± 0.3 16%	0.31 ± 0.06 20%	2.4 ± 0.7 28%

Table 2.19: *Statistical significance of differences in extent of contour interaction/crowding due to stimulus (L, LM and CM) and test (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding) when measured in stroke widths, optotype widths and minutes of arc.*

Units	**Stimulus**	**Test**	**Stimulus*Test**
Stroke widths	0.11	0.099	0.94
Optotype widths	0.098	**0.027**	0.92
Minutes of arc	**0.001**	0.68	0.90

A 3 (stimulus) $\times$ 4 (test) repeated measures ANOVA for each unit showed that the extent of contour interaction and crowding was not significantly different between stimuli and tests when the target-flanker separation was measured in stroke widths (see Table 2.19). The variance in extent across all stimuli was largest with minutes of arc and significantly different between stimuli [F(1.1,4.2)=61, p=0.001]. This was driven by the significantly larger (worse) visual acuity with CM than L and LM stimuli (see Section 2.4.4).

Measured in stroke widths, the extent of contour interaction and crowding across tests and stimulus conditions was $2.5{\pm}0.4$ stroke widths. These results (see Figure 2.24) indicate that the closest available placement of crowding features on commercially versions of the Kay Picture test (5 stroke widths) is outside the area where contour interaction is expected to occur (mean 3.9 ± 0.41 stroke widths for L Kay Pictures). On the Lea Symbols test, the closest available placement of crowding features on commercially available versions (3.5 stroke widths) is on the edge of the measured extent of contour interaction (mean 3.8 ± 0.45 stroke widths). With the HOTV test and Cambridge Crowding test, the closest placement of crowding features (2.5 stroke widths) is within the measured extent of contour interaction (mean 3.2 ± 0.64 stroke widths) and crowding (mean 2.1 ± 0.4 stroke widths) and therefore an effect of contour interaction and crowding is expected.

Extent of contour-interaction/crowding measured with a Tukey HSD planned comparison

The variance in extent of contour interaction and crowding (determined using a Tukey HSD planned comparison) across all stimulus conditions (L, LM and CM) and tests (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding test) was investigated to ensure the best units for defining the position of flankers (see Table 2.20). The total variance was smallest when the target-flanker separation was measured in stroke widths (15%) and largest when measured in minutes of arc (27%). The average variance within stimulus conditions was smallest for stroke widths (13%) and minutes of arc (13%).

Table 2.20: *The average extent of contour interaction and crowding measured with a Tukey HSD planned comparison ±1SE and the variance (SE/average) of contour interaction and crowding across stimulus conditions and tests for stroke widths, optotype widths and minutes of arc.*

	Stroke widths	**Optotype widths**	**Arcmin**
Standard luminance (L)	2.5 ± 0.9 35%	0.44 ± 0.20 45%	1.6 ± 0.6 41%
Luminance modulated (LM)	1.8 ± 0.3 20%	0.27 ± 0.05 13%	1.3 ± 0.2 21%
Contrast modulated (CM)	2.0 ± 0.0 0%	0.30 ± 0.06 19%	4.9 ± 0.2 4%
Average	13%	21%	13%
Total variance across all stimulus conditions	2.3 ± 0.3 15%	0.38 ± 0.08 20%	3.0 ± 0.8 27%

Measured extent compared to commercial tests

The commercially available Kay Picture test has the surrounding box either 0.5 or 1 optotype widths away from the target, which is equivalent to 5 or 10 stroke widths (see

Figure 2.24). The extent of contour interaction was measured to be 3.9 ± 0.4 or 2 stroke widths away (measured using Gaussian fits and Tukey HSD respectively) which suggests that no contour interaction would occur for adults on the commercially available version of the test. With the Lea Symbol and HOTV tests, the closest commercial placement of contour interaction features is 0.5 optotype widths which is 3.5 and 2.5 stroke widths, respectively. For both tests, the extent measured with the Gaussian fit is larger and suggests some contour interaction may occur, whereas using the Tukey HSD pairwise comparison indicates that no contour interaction would occur. The Cambridge Crowding test has a measured extent of crowding that is larger with both the Gaussian fit (2.8 ± 0.4 stroke widths) and the Tukey HSD pairwise comparison (5 stroke widths) than the flanking letter placement of 2.5 stroke widths and therefore a crowding is likely to occur.

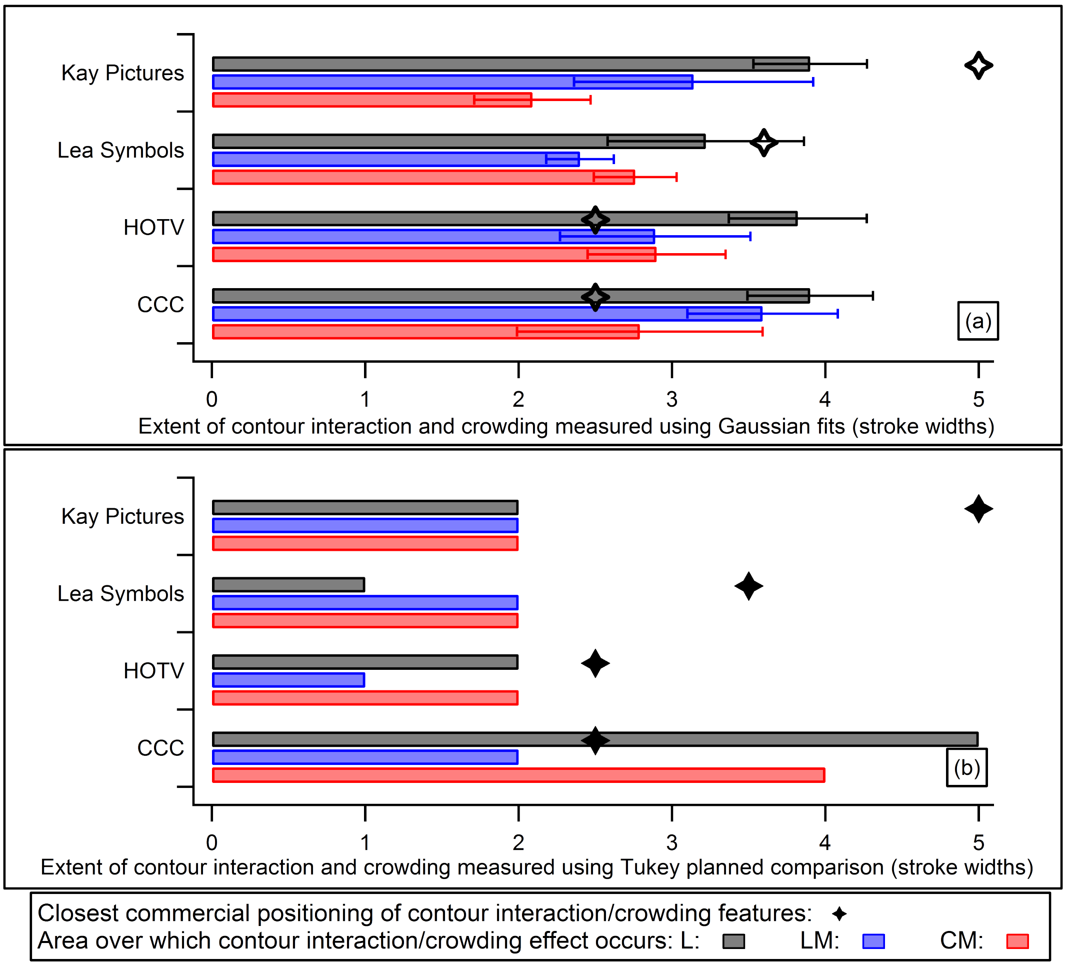


Figure 2.24: *Measured extents of contour interaction and crowding for L, LM and CM versions of Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding test (measured in stroke widths), calculated using (a) Gaussians (top), and (b) Tukey planned comparisons (below). The closest position of crowding features available on commercially available tests are shown by the black markers - a contour interaction/crowding effect on the commercially available chart would be expected if the black marker is within the area of the grey bar.*

2.4.8 Slopes of the psychometric functions

The slope of the psychometric function for a visual acuity test indicates the sensitivity of that test to changes in acuity. The slopes of the psychometric functions were estimated from Weibull function fits to psychometric performance data (for examples, see Figure 2.25) (Weibull, 1951), as has previously been applied in letter acuity studies (Alexander et al., 1997; Pelli et al., 1988). An example of how the slope is extracted from the pscyhometric function is shown in Figure 2.7. Psychometric function slopes across target-flanker separations are shown for different stimulus conditions (see Figure 2.26) and tests (see Figure 2.27) and averaged across different stimulus conditions and tests (see Figure 2.28).

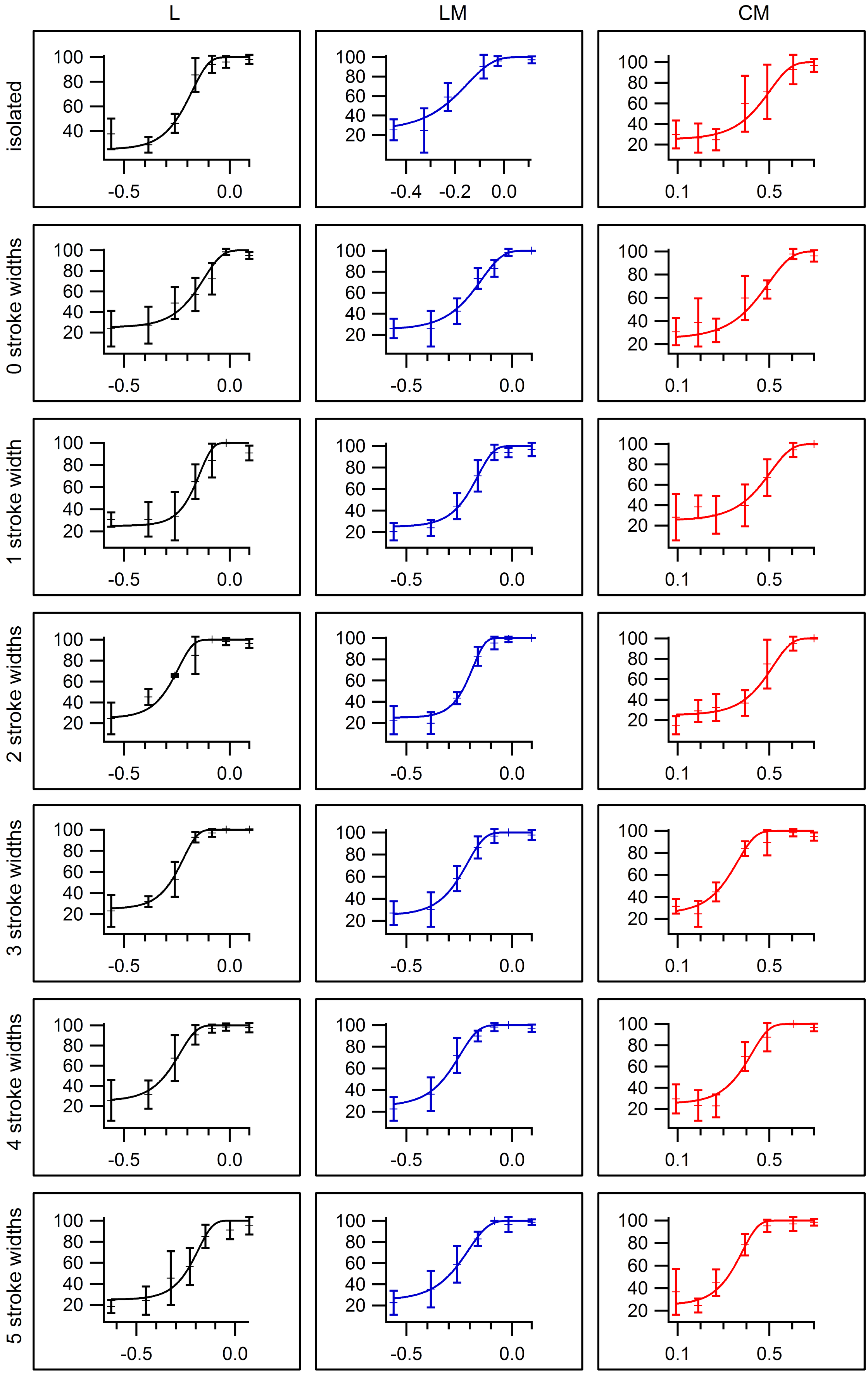


Figure 2.25: *Example psychometric functions for L, LM and CM stimulus conditions without flankers ("isolated") and when flankers were placed at 0, 1, 2, 3, 4 and 5 stroke-widths away from the target.*

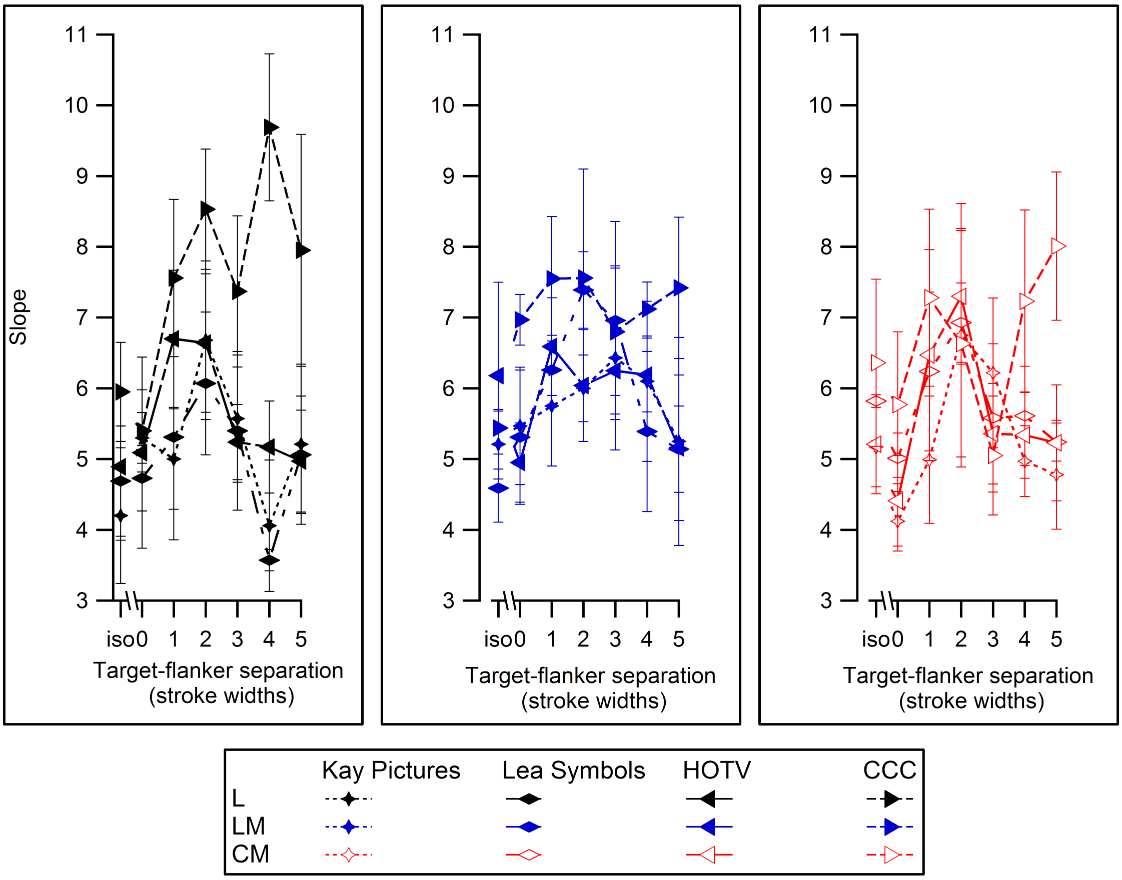


Figure 2.26: *Slopes of the psychometric function averaged across participants for the Kay Pictures, Lea Symbols, HOTV test and Cambridge Crowding test, in standard luminance (L), luminance-modulated (LM) and contrast-modulated (CM) forms, presented without flankers ("iso") and when flankers were placed at 0, 1, 2, 3, 4 and 5 stroke-widths away from the target. Error bars indicate* ±1*SE.*

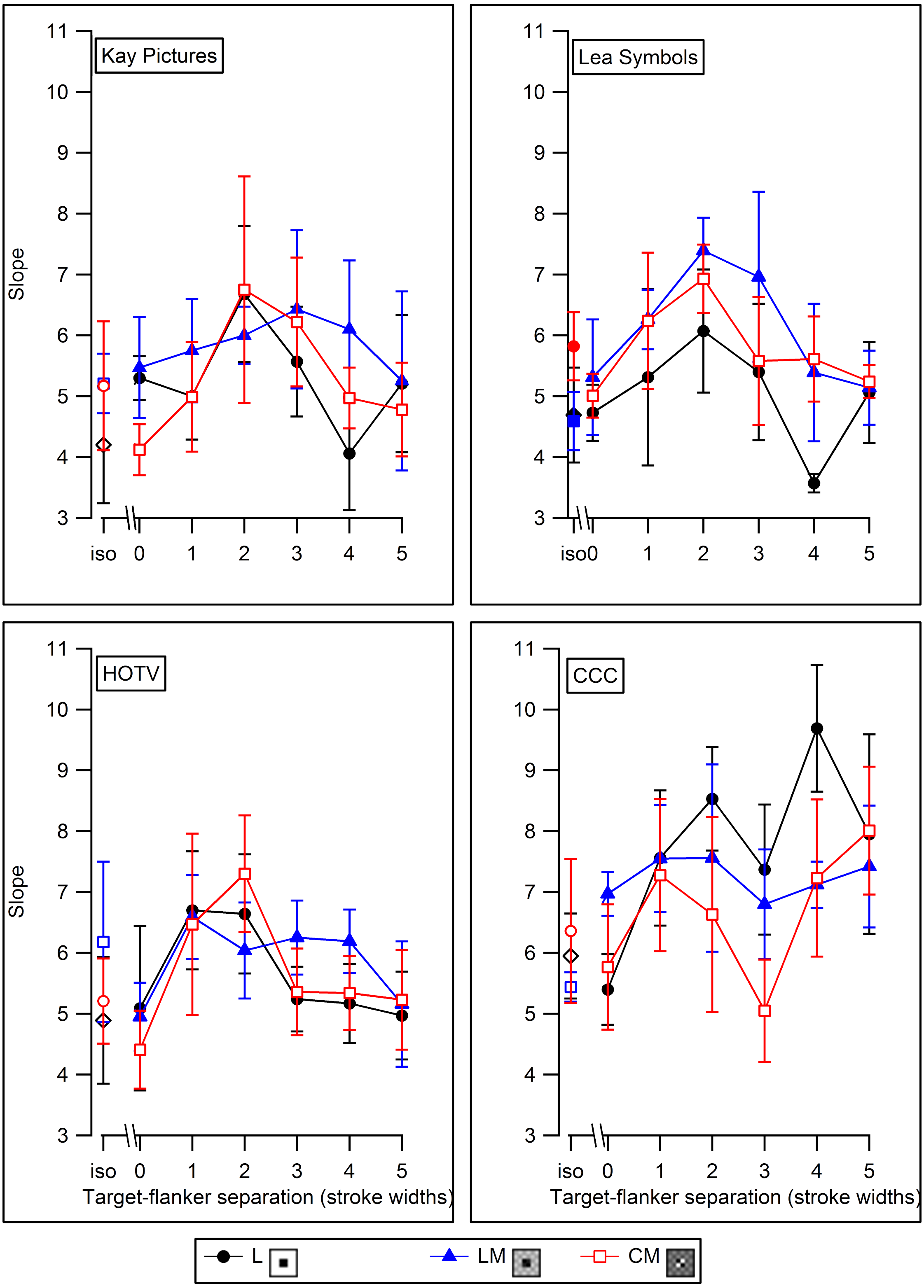


Figure 2.27: *Slopes of the psychometric function averaged across participants for the Kay Pictures, Lea Symbols, HOTV test and Cambridge Crowding test (CCC), in standard luminance (L), luminance-modulated (LM) and contrast-modulated (CM) forms, presented without flankers ("iso") and when flankers were placed at 0, 1, 2, 3, 4 and 5 stroke-widths away from the target. Error bars indicate ±1SE.*

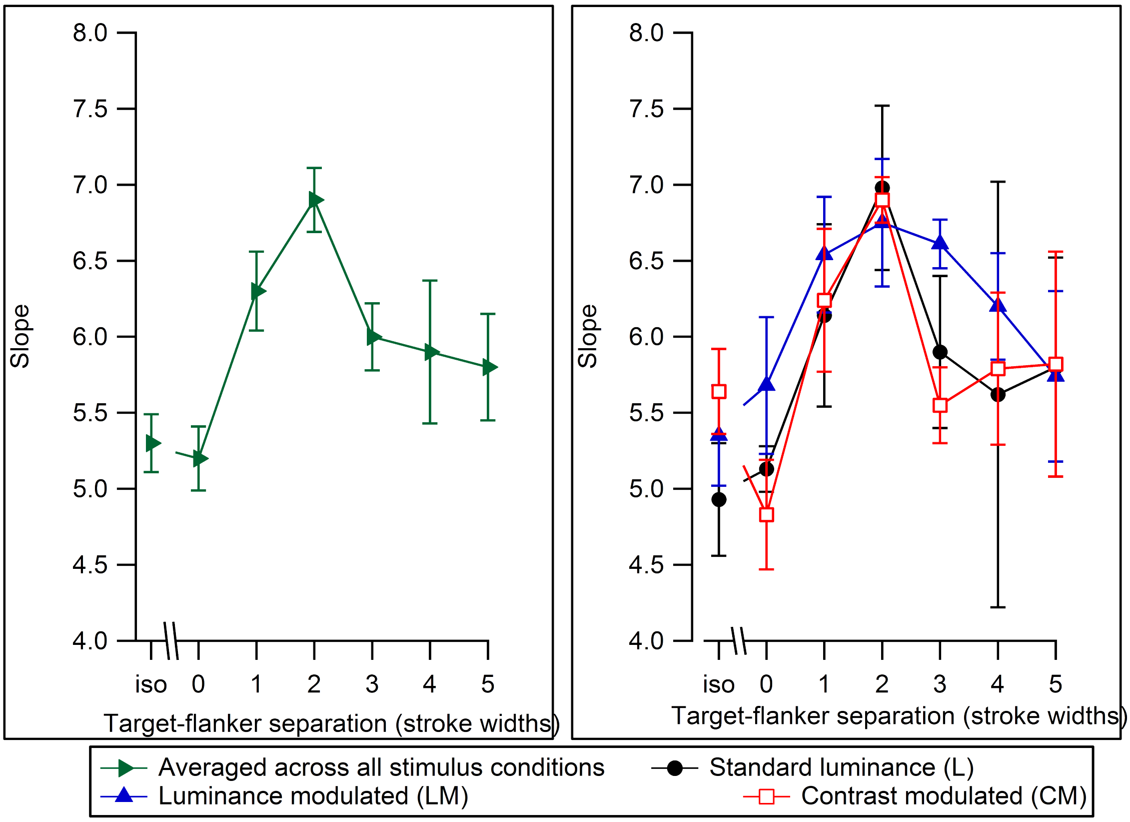


Figure 2.28: *Slopes of the psychometric function averaged across participants and stimulus conditions (L, LM and CM) plotted against target-flanker separations, for each of the four tests (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding test) (right) and averaged across all tests (left). Error bars indicate $\pm 1SE$.*

Assessment of the underlying psychometric function (see Table 2.21) found the steepness of slopes was significantly affected by target-flanker separation [F(4.2,17)=8.5, p=0.001] but not by stimulus condition (p>0.05) or test (p>0.05). Slopes were steepest with target-flanker separations of 1 stroke width (mean 6.3 ± 0.26) and 2 stroke widths (mean 6.9 ± 0.21) and least steep when there were no flankers (mean 5.3 ± 0.19) and when the target and flankers were abutting (mean 5.2 ± 0.21). A Tukey HSD pairwise comparison of target-flanker separations (see Table 2.21) shows significant differences in the steepness of psychometric function slopes only between 1 stroke width separation and the isolated condition (p=0.034) and abutting flankers (p=0.019).

Table 2.21: *Repeated measures ANOVA of psychometric function slopes.*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Stimulus	9.7	2.0	4.9	0.83	0.47	0.17
Error	47	8	5.9			
Separation	181	2.7	67	3.4	0.061	0.46
Error	211	11	20			
Separation	**210**	**4.2**	**29**	**8.5**	**0.001**	**0.68**
Error	56	17	3.3			
Stimulus*Test	30	6	5.0	0.71	0.64	0.15
Error	167	24	6.9			
Stimulus*Separations	21	4.8	4.4	0.39	0.84	0.090
Error	212	19	11			
Test*Separation	21	4.8	4.4	0.39	0.84	0.090
Error	76	18	4.2	1.4	0.17	0.26
Stim*Test*Sep	69	20	3.4	0.61	0.90	0.13
Error	452	82	5.5			

2.4.9 Bar flanker control experiment

Box versus bar flankers

The pattern of the magnitude of contour interaction with various target-flanker separations was consistent across test and stimulus condition for flanking bars and a surrounding box. Therefore averaged results across stimulus condition and test are shown in Figure 2.29a. The peak magnitude of contour interaction was similar with a surrounding box (0.061 ± 0.013 logMAR) and flanking bars (0.083 ± 0.038 logMAR) but the target-flanker separation at which the peak occurred was most commonly when the flankers were 1 stroke width away for bars and abutting for a surrounding box. Abutting target and flankers is not ideal as this would alter the overall optotype shape. Therefore the flanking bars are preferable to the surrounding box due to the maximum magnitude of contour interaction being at 1 stroke width separation.

Box, bar and letter flankers

The peak magnitude of contour interaction with the HOTV letters was similar with a surrounding box (0.062 ± 0.020 logMAR) and flanking bars (0.067 ± 0.009 logMAR). When averaged across all stimulus conditions the peak occurred with a separation distance of 0 with the surrounding box and 1 stroke width with flanking bars. A much larger peak magnitude of crowding was obtained with abutting flanking letters (mean 0.19 ± 0.02 logMAR). Averaged results are shown in Figure 2.29.

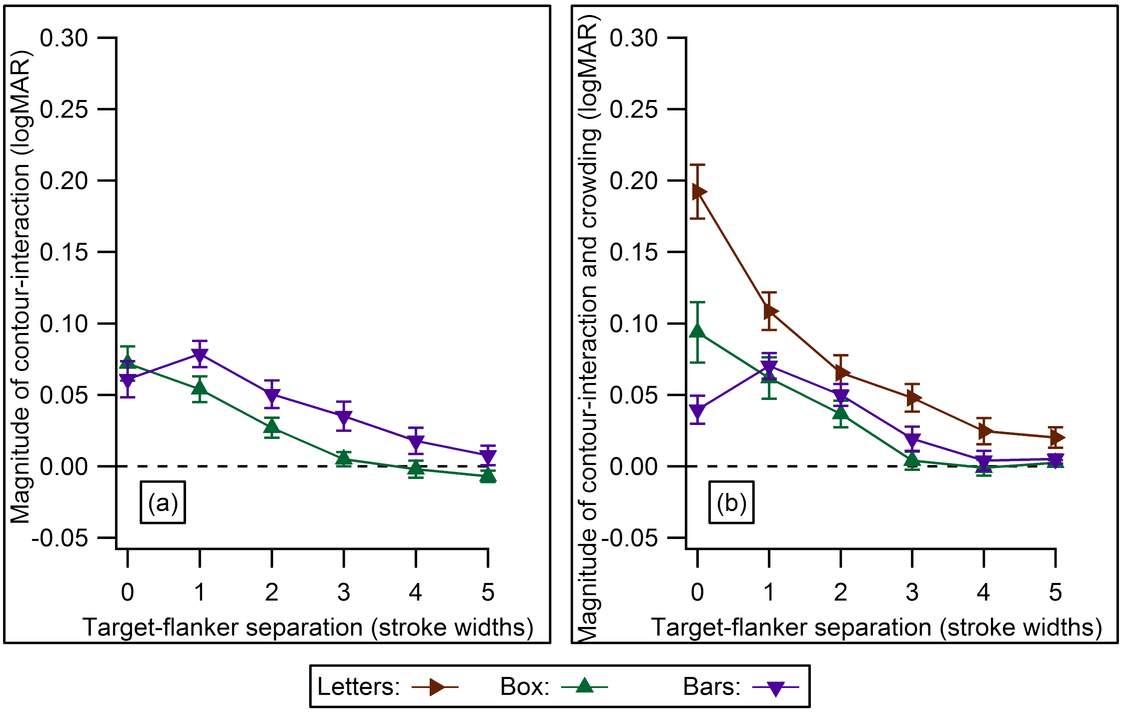


Figure 2.29: *The magnitude of contour interaction with a box and bars with the Kay Pictures, Lea Symbols and HOTV tests (a) and the magnitude of contour interaction/crowding with the HOTV letters with a surrounding box, flanking bars and flanking letters (b) for each of the target-flanker separations from 0 (abutting) to 5 stroke widths. Error bars indicate* $\pm 1SE$

2.5 Discussion

2.5.1 Visual acuity

Visual acuity measured is affected by the target optotype (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowded) the stimulus condition (L, LM and CM) and separation of contour interaction or crowding features. Visual acuity measured with CM stimuli was significantly worse (mean 0.55 ± 0.05 logMAR) than when measured with LM stimuli. There is evidence that CM stimuli are processed in a more binocular region (Hairol and Waugh, 2010; Wong et al., 2001, 2005) , possibly in V2 (Sheth et al., 1996; Wong et al., 2001) or higher (Calvert et al., 2005; Larsson et al., 2006; Chung et al., 2007, 2008*a*). The receptive field sizes in V2 and above appear to be 2 to 3 times larger than the receptive field sizes in V1 (Smith et al., 2001) which is supported by evidence of spatial summation areas that are 2 to 3 times larger (Sukumar and Waugh, 2007). This would equate to 0.3-0.5 logMAR change in acuity, which is in line with the 0.28 ± 0.04 logMAR ($2\times$ larger) found by Hairol et al. (2013) with a rotated C and similar to the 0.55 ± 0.05 logMAR acuity difference found in this study with CM compared to LM stimuli. One reason for the larger difference found in this study and those found by Hairol et al. (2013) is that Hairol et al. (2013) used equally visible stimuli, whereas this study did not. Using equally visible LM and CM stimuli is preferable but would not be feasible in a clinical environment because this would involve adjusting the visibility of the stimuli for each person, which would likely be too time consuming, especially with children. Before creating equally visible stimuli, Hairol et al. (2013) measured visual acuity thresholds also using a higher contrast LM C ($l = 0.6$, in the current study $l = 0.7$) and a high contrast C ($m = 3.0$, in this study $m = 3.5$) which resulted in a 0.44 ± 0.04 logMAR (2 to $3\times$ larger) acuity difference. Another factor that could have contributed to the larger difference in acuity measured between LM and CM stimuli with this study compared to that found by Hairol et al. (2013) with a rotated C was that the exposure duration was shorter with the rotated C (400ms) than with this study (unlimited exposure duration) which may have affected acuity with the LM stimuli more than with the CM stimuli.

Visual acuity measured with LM stimuli was significantly higher (p< 0.001) than when measured with L stimuli but the acuity difference between LM and CM was much larger than the difference between L and LM (0.06 ± 0.01 logMAR, equivalent to about half a line on a visual acuity chart). The LM stimuli, unlike the L stimuli, have incorporated noise. Incorporated noise which is above the estimated internal noise level of the participant (equivalent noise) raises the detection threshold (Pelli and Farell, 1999) and could explain the higher (worse) acuity thresholds for the noisy LM stimuli (than for noiseless L stimuli) in this study. There is evidence of reduced high-noise efficiency in amblyopes (Pelli, Levi and Chung, 2004), which can be measured by comparing thresholds measured with and without white noise (Pelli and Farell, 1999). Pelli, Levi and Chung (2004) suggest that the difference in logMAR visual acuity measured with and without noise is useful for diagnosing amblyopia due to the loss of high-noise efficiency in amblyopia, which they found to be 1 to 2 lines for amblyopes and less than one line for normals. In this experiment only normals were used and less than one line difference was found with and without noise (0.06 ± 0.01 logMAR).

The results of the present study using single presentations of four optotypes for each test, indicate that visual acuity for Kay Pictures is 1 to 2 lines better with L stimuli than when measured using Lea Symbols, HOTV letters or a Cambridge Crowded arrangement of letters. This result is in agreement with previous studies in which visual acuity was measured with the full set of Kay Pictures and other tests, all in their commercially available configurations (Jones et al., 2003; Shah et al., 2012; Formankiewicz and Waugh, 2013; Anstice et al., 2017*b*). The same 1 to 2 line difference was found with LM stimuli. With CM stimuli, the Kay Picture test still gave the lowest (best) visual acuities but the difference was smaller (about half a line). The Kay Picture optotypes have the most detail in them, which may be the main reason for the lower (better) acuity measurements compared to the other tests. However, with the CM stimuli likely being processed in V2 or above (Sheth et al., 1996; Wong et al., 2001; Calvert et al., 2005; Larsson et al., 2006; Chung et al., 2007, 2008*a*), which have larger receptive field areas (Smith et al., 2001) and the consequent larger spatial summation areas (Sukumar and Waugh, 2007) it is likely that some of this detail would be lost, resulting in a smaller difference in measured acuity with CM stimuli between tests.

2.5.2 Contour interaction and crowding

The closest positioning of flankers on commercially available visual acuity tests is most commonly 0.5 optotype widths. The results of this study and the findings of others, suggest that the affect of flankers at 0.5 optotype widths is unlikely to result in any contour interaction or crowding at least in adults and the effects would be enhanced if flankers were placed closer to the target (Formankiewicz and Waugh, 2013; Song et al., 2014). Results from this study extend this finding to single target presentations of letters, pictures or symbols and to LM and CM stimuli. It should be noted that the Kay Picture test used in these experiments used the original Kay Picture optotypes. A newer version was released with redesigned optotypes, with the target-flanker distance specified in stroke widths (2.5 stroke widths) and with the flanker placement closer to the target than the previous 5 stroke widths (Newsham et al., 2016). The results of the current study suggest that this new specification in stroke-widths is a good improvement to this test, however these results would also advise use of bars, rather than a box, and closer placement of the surround.

The position of flankers on most commercially available acuity tests is specified in proportion to the target optotype size (Atkinson et al., 1988; McGraw and Winn, 1993; Holmes et al., 2001; Jones et al., 2003). This metric produces crowding extents that are more variable than when units of stroke width are used. When specified in optotype widths, a placement of 0.5 optotype widths corresponds to 2.5 stroke widths for the HOTV test and Cambridge Crowding test, 5 stroke widths for the Kay Pictures test and 3.5 stroke widths for the Lea Symbols test. This variability makes it difficult to reliably compare crowded visual acuity results across test. The results of this study suggest that use of stroke width, rather than optotype width to specify the position of flanking features, leads to more consistent crowding effects across tests. The extent of contour interaction when measured in stroke widths or gap widths (which are equivalent units) is not significantly different between LM and CM stimuli, as was also found by Hairol et al. (2013). Therefore, specifying the flanker placement in stroke widths is most useful if using a set distance across all tests and stimuli.

In line with the results of others (Danilova and Bondarko, 2007; Bedell et al., 2013; Siderov et al., 2012) use of units of arcmin reveal a small extent of foveal crowding, with consistency across tests similar to that found with units of stroke width but a significantly larger extent of contour interaction/crowding across stimuli (p=0.001) with a larger extent with CM (4.9 ± 1.4 arcmin) than with L (1.6 ± 0.5 arcmin) and LM (0.91 ± 0.20 arcmin) stimuli. It has been suggested (for example by: Flom, Weymouth and Kahneman, 1963;

Flom, Heath and Takahashi, 1963; Toet and Levi, 1992; Levi, 2008; Siderov et al., 2012) that foveal crowding only occurs over small distances (up to 4-6 arcmin). The data in this study fall within this foveal spatial zone. For all tests and stimuli, the target and flanker/s are within this 6arcmin area with the exception of the CM Cambridge Crowded test, for which only 48% of the flanking letters would fit in this zone assuming an abutting target and flanker, or a 1 stroke width target-flanker separation. If foveal crowding in normal adults does only occur within a set 6arcmin spatial zone, then this could explain why there is no difference between the magnitude of contour interaction and crowding with CM stimuli. However, peripheral crowding occurs over larger areas (Toet and Levi, 1992; Kooi et al., 1994; Levi, 2008; Coates et al., 2013) and the normal periphery can be used to simulate strabismic amblyopia (Hariharan et al., 2005; Hussain et al., 2012). This could mean that in amblyopia the zone is larger, so that the difference between contour interaction and crowding would be expected to occur. These results support the suggestion in recent papers that standard luminance tests that aim to screen for amblyopia should incorporate letter flankers to increase the effect of crowding (Formankiewicz and Waugh, 2013; Song et al., 2014). However, a target letter surrounded by other letters may be too complicated for some young children. The results of the current study show that simple contours placed around a single target letter, symbol or picture, close to but not abutting the target, also produce significant degradative effects on visual acuity.

The peak magnitude of contour interaction was similar for picture/symbol and letter optotypes with L (~ 1 line on a letter chart), LM ~ 1 line) and CM (~ 1.5 lines) stimuli. This finding of a greater peak magnitude of contour interaction with CM compared to LM has previously been found with rotated square Cs (Hairol et al., 2013) and contrast thresholds for large letters (Chung et al., 2007, 2008*a*) but has not previously been investigated with optotypes and a setup suitable for use in a clinical environment with young children. Using a more clinically suitable setup, the difference in the peak magnitude of contour interaction between LM and CM is smaller (0.05 logMAR) than was found by Hairol et al. (2013) (0.12 logMAR), which could be due to differences in the stimuli in this study (e.g. not equally visible stimuli, optotype recognition instead of orientation discrimination, optotype design and unlimited exposure duration). The differences in stimuli, task and exposure duration could all potentially affect flanked CM stimuli more than flanked LM stimuli, leading to more contour interaction with LM and CM than has been found in the current study and also a larger discrepancy in LM and CM peak magnitude of contour interaction. Bars abutting a square C, as used by (Hairol et al., 2013), especially with a short exposure duration, is likely to make detection of the gap more difficult than shape recognition with an abutting box. Chung et al. (2007, 2008*a*) found more crowding with low contrast large letter trigrams when they were contrast modulated than when they were luminance modulated. If there is a specific deficit in processing contrast modulated images, as has previously been suggested (for example by: Wong et al., 2001; Chung et al., 2008*a*; Hairol et al., 2013) and contour interaction/crowding is greater in amblyopes, as has previously been suggested (for example by: Mayer and Gross, 1990; Morad et al., 1999; Hess et al., 2001; Levi, Hariharan and Klein, 2002), then a greater magnitude of contour interaction with contrast modulated stimuli in people with normal vision indicates that crowded contrast modulated optotypes could be beneficial clinically for diagnosing amblyopia.

2.5.3 Slopes of psychometric function

The slope of the psychometric function for a visual acuity test indicates the sensitivity of that test to changes in acuity. The slopes of the underlying psychometric function were steeper under crowded conditions than for an isolated target, especially when the flankers were 1 or 2 stroke widths away from the target. It is interesting to note that steepest slopes do not coincide exactly with the point of the peak magnitude of contour interaction/crowding, which occurred at 0 or 1 stroke widths separation, but occur at slightly further target-flanker separations. Although not statistically significant, psychometric function slopes are steeper for the Cambridge Crowding test arrangement than for the other three tests.

2.5.4 Implications of the results

The current study used single presentations of letter, picture and symbol optotypes designed primarily for use in children but the experiments were carried out on adult participants due to the number of conditions involved, an approach also taken by other researchers (Candy et al., 2011; Little et al., 2012; Song et al., 2014; Anstice et al., 2017*b*; Paudel et al., 2017). Although visual acuities are worse in young children than adults, the relationship between tests used to measure these acuities has been found to be similar (Candy et al., 2011; Mercer et al., 2013). Although this has not previously been specifically tested with LM and CM stimuli, the inter-test relationships found in the current study for these stimulus types were similar, or reduced for CM versus LM stimuli. Therefore, the inter-test comparisons made with results obtained with adults, which may require lengthy psychophysical procedures and numerous testing conditions, may be extrapolated to children, for whom the tests were primarily designed. This enables a small subsection of conditions to be used in Experiment 2 with children.

It has been reported that contour interaction and crowding is more extensive and of greater magnitude for children than for adults (Atkinson et al., 1986, 1988; Jeon et al., 2010; Masgoret et al., 2011; Norgett and Siderov, 2014). Therefore, if the target-flanker separation is chosen where adults demonstrate crowding/contour interaction for all 3 stimulus types (L, LM and CM), then the children in Experiment 2 also ought to, although the characteristics of contour interaction and crowding could be different to those in adults (Atkinson et al., 1986; Kovács, 2000; Scherf et al., 2009). For both children and adults, visual acuity for letter targets improves systematically as the flankers move away from the target (Bondarko and Semenov, 2005; Norgett and Siderov, 2014), producing similar crowding function shapes. Therefore, placing the crowding features close to the target should still result in a large magnitude of contour interaction and crowding for the children in Experiment 2.

2.6 Conclusions

In summary, the results of Experiment 1 indicate that (1) the placement of surrounding features reveal more consistent crowding if they are specified in stroke widths, (2) placing crowding features 1 stroke width away will maximise the effects of contour interaction and crowding and result in a steeper slope of the underlying psychometric function thereby increasing sensitivity, (3) using flankers that are similar to the target optotype produces greater crowding and increases the sensitivity of the test with L and LM but not necessarily with CM stimuli in normal adults. For Experiment 2 (normal children) an edge-to-edge target-flanker separation of 1 stroke width will be used with L, decrement LM and increment CM tests.

Chapter 3

Experiment 2: Normal Children

3.1 Introduction

Visual acuity is routinely measured by clinicians as part of ocular health and visual function assessment, and during pre-school vision screenings. Detection of amblyopia, a developmental disorder affecting approximately 3.5% of adults (Flom and Neumaier, 1966; Attebo et al., 1998; Flynn et al., 1998, 1999; Robaei et al., 2006; Williams et al., 2008; Elflein et al., 2015), is a key reason for pre-school vision screening (Friendly, 1978; U.S. Preventative Services Task Force, 2004; Kemper et al., 2005; Bodack et al., 2010; Schlenker et al., 2010; UK National Screening Committee, 2013; Solebo et al., 2013; Jonas et al., 2017) because treatment is more likely to be successful if initiated early in life (Flynn et al., 1998, 1999). Inter-ocular visual acuity differences are a key component of amblyopia diagnosis and monitoring of treatment outcomes (Flom and Neumaier, 1966; Attebo et al., 1998; Flynn et al., 1998, 1999; Simons, 2005; Holmes and Clarke, 2006).

Visual acuity testing of pre-verbal infants and children is normally limited to Forced-choice Preferential Looking (FPL) using a grating on one side of a card and a plain grey on the other (for example: Teller Acuity Cards or the Keeler Acuity Cards), where the infant looks towards the grating because it is more interesting than the plain grey card. The Teller Acuity Cards are designed for use with 3-36 month olds however older children over 2 years old can be difficult to test with gratings (Clifford-Donaldson et al., 2006; Johnson et al., 2009). Grating acuity cards are good at identifying normal vision but some poor vision, such as refractive error and strabismus, can be missed by grating acuity cards

(Spierer et al., 1999; Hall et al., 2000; Drover et al., 2009) therefore optotype acuity is preferable wherever possible (Drover et al., 2009). For verbal but pre-literate children, or adults who cannot communicate using the Latin alphabet, a range of visual acuity tests are available, which are summarised in Chapter 1 (Literature Review).

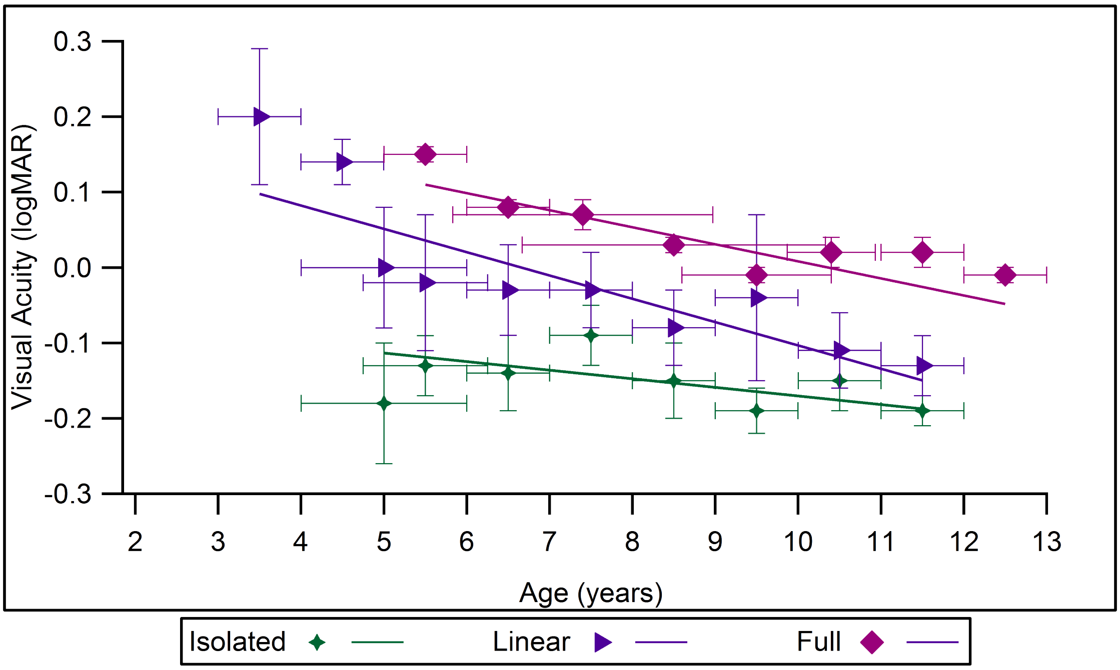


Figure 3.1: *Visual acuity measurements of 2-13 year olds using individual letter optotypes ("isolated"), lines of letter optotypes ("linear") and full charts with multiple lines of letter optotypes ("full chart"). Data extracted from (Simmers et al., 1997; Myers et al., 1999; Manny, 2003; Chen et al., 2006; Stewart et al., 2006; Drover et al., 2008; Dobson et al., 2009; Pan, Tarczy-Hornoch, Cotter Susan, Wen, Borchert, Azen and Varma, 2009; Langaas, 2011; Norgett and Siderov, 2011; Leone et al., 2014).*

Visual acuity tests vary in the type of optotypes chosen, i.e. letters, symbols or pictures, and their arrangement on the test, i.e. a single optotype, a line of optotypes, or a full chart (multiple lines of optotypes displayed together). Both the type and design of the optotypes and the test format can influence visual acuity measurements (Anstice and Thompson, 2013). As indicated in Figure 3.1, measured visual acuity is lowest (best) when individual isolated optotypes are displayed (Morad et al., 1999) and highest (worst) when multiple lines of optotypes (full charts) are used. Differences in acuity measurements are likely to be partially due to the cognitive complexity of the task (reading multiple lines is much harder for a young child than identifying a single isolated optotype) and partially due to the presence of contour interaction (with flanking bars) and crowding (with nearby optotypes).

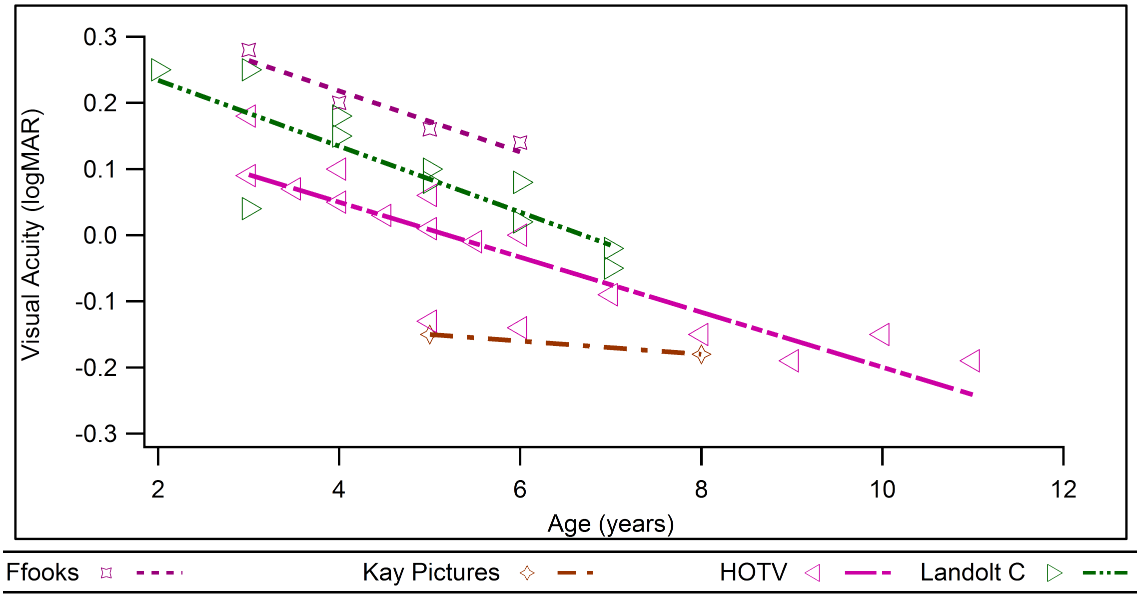


Figure 3.2: *Visual acuity measurements of 2-12 year olds taken from other studies using isolated Ffooks Symbols (Keith et al., 1972), Kay Pictures (Norgett and Siderov, 2011), HOTV/HOVXYU letters (Lippmann, 1971; Langaas, 2011; Leone et al., 2014) and Landolt C (Kitao, 1960; Atkinson and Braddick, 1982; Spekreijse, 1983; Fern and Manny, 1986) optotypes displayed individually. Error bars not shown due to lack of availability of the necessary data. Data were obtained without any contour interaction features.*

As indicated in Figure 3.2, even for isolated optotypes, visual acuity measurements can vary between tests. This is apparent when comparing visual acuity measurements across studies (e.g. Figure 3.2) and within studies across test (for example: Candy et al., 2011; Woodhouse et al., 2013; Anstice and Thompson, 2013; Formankiewicz and Waugh, 2013; O'Boyle et al., 2016; Anstice et al., 2017*b*). The lowest (best) acuities shown in Figure 3.2 were obtained using the Kay Picture optotypes, which have been shown to overestimate visual acuity in adults also in the standard linear format (for example by: Jones et al., 2003; Shah et al., 2012; Anstice et al., 2017*b*). Candy et al. (2011) found inter-test acuity differences in adults as well as differences in discriminability of individual optotypes for them.

Letter tests appear to produce higher (worse) acuities with young children when the task is to identify the orientation of the letter than when the task is to identify the letter (see Figure 3.3). This is most likely due to directional sense, which is immature up to 7 years of age. Up-down discrimination is commonly problematic up to 5 years of age and left-right discrimination is commonly problematic up to 7 years of age. Difficulties with direction can be problematic even when pointing or matching the intended direction

(Hanfmann, 1933; Newhall, 1937; Wechsler and Pignatelli, 1937; Graham and Berman, 1960; Sheridan, 1960; Teuber, 1963; Cairns and Steward, 1970).

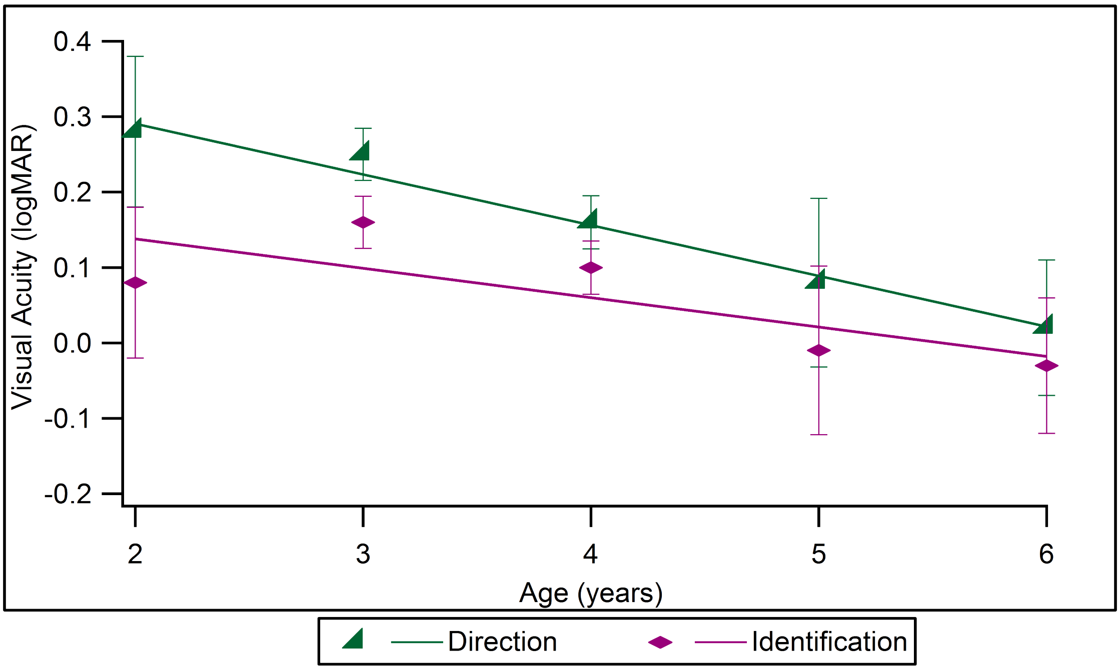


Figure 3.3: *Visual acuity measurements of 2-6 year olds using letters where the task is to indicate the direction (Direction) (Kitao, 1960; Atkinson and Braddick, 1982; Spekreijse, 1983; Fern and Manny, 1986) or identifying the letter (Identification) (Lippmann, 1971; Langaas, 2011; Leone et al., 2014).*

3.1.1 Adult-like visual acuities

Estimates of the age at which visual acuity becomes adult-like (see Figure 3.4) are younger (range: 2 to 6 years old, median: 5 years old) when measured with isolated optotypes (Catford and Oliver, 1973; Mayer et al., 1982; Atkinson and Braddick, 1982; Atkinson et al., 1986; Birch and Hale, 1988; Neu and Sireteanu, 1997; Ellemberg et al., 1999; Stiers et al., 2003) than when there are contour interaction or crowding features (range: 5 to 10 years old, median: 6 years old) (Atkinson and Braddick, 1982; Atkinson et al., 1986; Semenov et al., 2000; Lai et al., 2007; Drover et al., 2008; Doron et al., 2015). Atkinson et al. (1986) obtained adult-like acuities from 5 year olds with isolated but not crowded optotypes, further supporting the theory that visual acuity becomes adult-like earlier with isolated optotypes than when there are contour interaction or crowding features present.

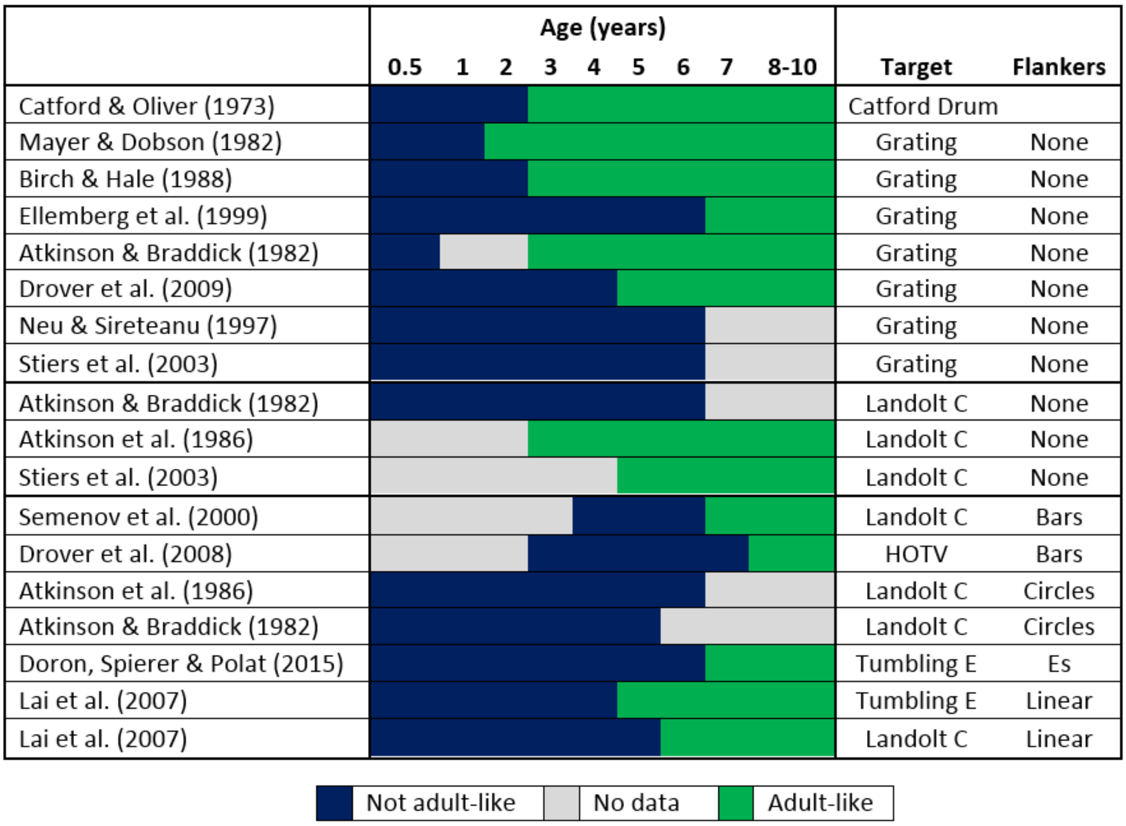


Figure 3.4: *Age at which visual acuities are adult-like for standard luminance acuity tests from published literature. Data taken from (Catford and Oliver, 1973; Mayer et al., 1982; Atkinson and Braddick, 1982; Atkinson et al., 1986; Birch and Hale, 1988; Neu and Sireteanu, 1997; Ellemberg et al., 1999; Semenov et al., 2000; Stiers et al., 2003; Lai et al., 2007; Drover et al., 2008, 2009; Doron et al., 2015).*

3.1.2 Contour interaction and crowding

Most studies investigating contour-interaction and crowding have used a 0.5 optotype width target-flanker separation distance, which matches that used in most commercially available pre-literate visual acuity charts. The results of Experiment 1 show that for adults, there is a small, not statistically significant contour interaction or crowding effect when the target optototype is flanked by a box or letters placed 0.5 optotype width away (average of 0.005 ± 0.003 logMAR). However, it has been reported (see Figure 3.5) that contour interaction and crowding is more extensive and of greater magnitude for children than for adults (Atkinson et al., 1986, 1988; Semenov et al., 2000; Bondarko and Semenov, 2005; Jeon et al., 2010; Masgoret et al., 2011; Norgett and Siderov, 2014). For both children and adults, visual acuity improves as the flankers move away from the target (Bondarko and Semenov, 2005; Norgett and Siderov, 2014).

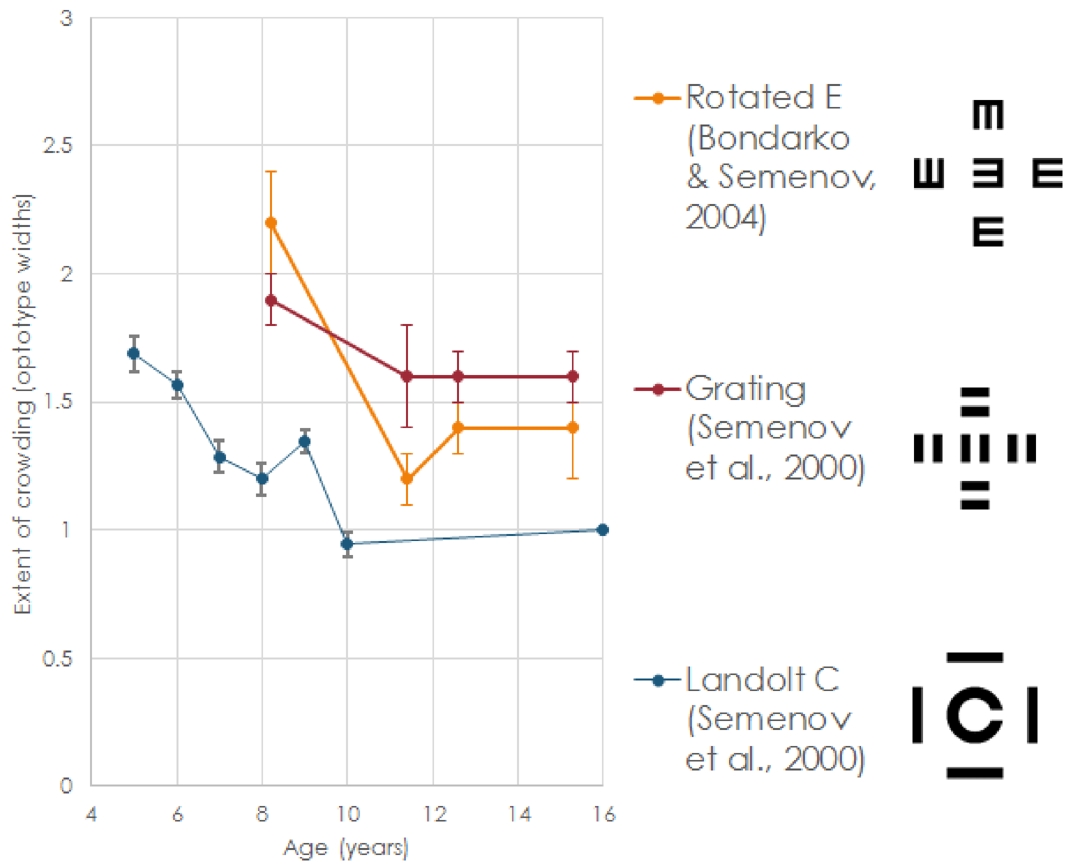


Figure 3.5: *The extent of contour interaction and crowding in 5-16 year olds. Data taken from Semenov et al. (2000) and Bondarko and Semenov (2005).*

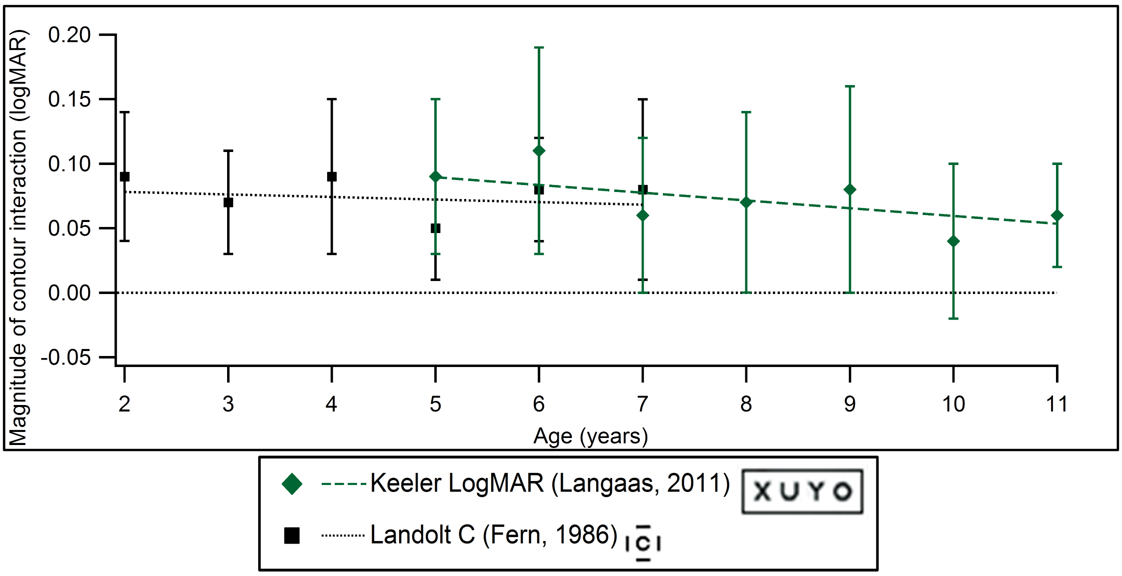


Figure 3.6: *Contour interaction in children (with a 2.5 stroke width separation) calculated from data extracted from Langaas (2011) by subtracting isolated letter acuities from those obtained with the Keeler logMAR test (formerly Glasgow Acuity Cards)and from Fern and Manny (1986) by subtracting acuities measured with an isolated Landolt C from acuities measured with flanking bars. Error bars indicate ±1SD.*

Fern and Manny (1986) measured visual acuity in 2 to 7 year olds using Landolt Cs with and without flanking bars (2.5 stroke width/0.5 optotype width target-flanker separation distance). Calculating the magnitude of contour interaction from their data (see Figure 3.6) indicates a magnitude of contour interaction (0.077 ± 0.006 logMAR) that is fairly consistent across age from 2 to 7 years. This magnitude is similar to the average magnitude of contour interaction obtained in normal adults with L optotypes in Experiment 1, with 2 and 3 stroke width target-flanker separations (0.053 ± 0.007 logMAR). Langaas (2011) measured acuities with 5 to 11 year olds using isolated letters and the Keeler LogMAR test (formerly Glasgow Acuity Cards). This test has 4 letters in a line with a surrounding box placed at 0.5 optotype width away. Calculating the contour interaction and crowding effects from the data shows a larger effect with the 5 (0.09 ± 0.06 logMAR) and 6 (0.11 ± 0.08 logMAR) year olds, and smaller effects with the 10 (0.04 ± 0.06 logMAR) and 11 (0.06 ± 0.04 logMAR) year olds. Taken together, these results suggest that contour interaction effects might be consistent from age 2 years, but crowding reduces with age. If the magnitude of contour interaction does not change with age (above 2 years old) then it would be expected that the age at which visual acuities are adult-like with and without contour interaction features would be identical. However, this has not been demonstrated. This inconsistency in the literature remains to be resolved.

The magnitude of crowding (measured with letters flanked by letters with a 0.5 optotype width separation) was significantly larger than with adults for 3 to 4 year olds but not for 5 to 7 year olds (Atkinson and Anker, 1988; Atkinson et al., 1988). Due to the 3 to 4 year olds finding the task of identifying the letter too cognitively taxing, Atkinson and Anker did a 2AFC (2-alternative forced-choice) version with the 3 to 4, but not 5 to 7 year olds, in which two cards were shown and the task was to identify which one had an "O" as the central letter. Acuities tested using both methods were not significantly different when tested on adults, however the methods were not directly compared in children. Ideally these crowding effects would be assessed using the same task and the same targets in children and adults. The current study aims to do that.

3.1.3 Contrast-defined images

Bertone et al. (2010) measured contrast thresholds for detecting the direction of the gap in a large Landolt C and found adult-like contrast thresholds in 12 year olds with LM but not CM targets. However, with an orientation discrimination task, acuities are equally immature for LM and CM static gratings with 5 year olds (Lewis et al., 2007) and 5 to 10 year olds (Bertone et al., 2008). Research done on the decline of visual processing in normal ageing may give indications regarding what happens with early development as more complex processing tends to develop later (Daw, 1998) and deteriorate with age earlier (Faubert, 2002). Tang and Zhou (2009) found that contrast sensitivity declined earlier but more slowly with CM, compared to LM, gratings and Habak and Faubert (2000) found a larger contrast sensitivity deficit with older participants (aged 64 to 79 years old) compared to younger participants (21 to 26 years old) with CM gratings, than LM gratings. This earlier decline with normal ageing might potentially mean that with normal early development, CM acuity develops later.

In Experiment 2 visual acuities using standard luminance (L), luminance-modulated (LM) and contrast-modulated (CM) letters and symbols were measured in normal children aged 3 to 16 years of age. The magnitude of contour interaction and crowding with optimum placement, was also assessed in these children. The results of Experiment 2 will determine a normal time-course for the development of L, LM and CM acuities and assess the magnitude of contour interaction and crowding with L, LM and CM optotypes. These data will provide a basis from which to work for studies, especially for those clinicians who might wish to test amblyopic children with CM optotypes, but also to those wishing to work with single L pictures, symbols or letter optotypes, surrounded by a box or other optotypes.

3.1.4 Staircase design

To assess visual acuity, contour interaction and crowding across age, the same optotypes and testing paradigm should be used. The staircase method is an efficient (Cornsweet, 1962) and popular (for example: Atkinson et al., 1986; Bach, 1996; Baker et al., 2007; Tang and Zhou, 2009) method of determining an accurate visual acuity threshold (Corwin et al., 1979). Whilst the method of constant stimuli (Urban, 1910) combined with forced-choice psychophysics gives detailed information about thresholds and slopes of the underlying psychometric functions for visual acuity and minimises observer expectation and bias (Klein, 2001), the time taken to obtain each visual acuity estimate is far longer than with the staircase method. The stairccase method is therefore more appropriate with young children (Witton et al., 2017) and in clinical settings.

There are four main factors identified by Cornsweet (1962) that should be considered when constructing a staircase:

1. where the staircase should start: above, below or on the estimated threshold;
2. the step size;
3. how many reversals until the staircase terminates;
4. if and when the step size changes.

A staircase may also include "catch" trials that do not contribute to threshold calculations (Bach, 1996) to encourage responses and monitor attention levels.

The number of reversals chosen to contribute to final threshold estimation needs to be a compromise between keeping the length of the staircase short, so maintaining the attention of the child, but avoiding overestimating visual acuity thresholds by having too few reversals (Witton et al., 2017). Examples of research studies that have used a staircase method commencing with an easily visible optotype size, combined with ignoring the first two reversal points when calculating final thresholds, are provided in Table 3.1. Step size and numbers of reversals were varied and tested in a pilot experiment before the main experiment was conducted.

3.2 Aims

The aims of the pilot experiments were to determine suitable staircase parameters for use with normal children (for the main experiment) and to compare visual acuities obtained with the method of constant stimuli (used in Experiment 1) and the staircase method (used in Experiment 2).

Table 3.1: *The designs of staircases used in similar research.*

Paper	Starting point relative to estimated threshold	Number of reversals	Number of reversals averaged	Reversals not averaged
Aaen-Stockdale et al. (2007)	Supra	8	6	Initial 2
Jeon et al. (2010)	Supra	10	6	Initial 2
Johnston et al. (1994)	Supra	12	10	Initial 4
Levi and Li (2009*b*)	Supra	8	6	Initial 2
McKee et al. (2003)	Supra	6	4	Initial 2
O'Connor et al. (2010)	Supra	8	6	Initial 2
Simmers (2003)	Supra	8	6	Initial 2
Watanabe et al. (2004)	Supra	12	6	Initial 2

In the main experiment, the aims are to:

1. determine visual acuities of normal children aged from 3 to 16 years using L, LM and CM versions of individually presented Kay Pictures, Lea Symbols, HOTV and Cambridge Crowded test optotypes. In this way, normal acuity, particularly for CM optotypes, across age groups will be determined for the first time. Age at which visual acuities are adult-like will be estimated.

2. determine the magnitudes of contour interaction and crowding with optimally placed surrounding features using with L, LM and CM stimuli in normal children. The magnitude of contour interaction and crowding with optimally placed surrounding features, particularly for CM stimuli, will be measured across age for normal children for the first time. Age at which contour interaction and crowding effects are adult-like will be estimated.

3.3 Methods

3.3.1 Apparatus

The apparatus setup is the same as that described in Experiment 1.

3.3.2 Participants

All experiments were carried out in accordance with the Code of Ethics of the World Medical Association in the Declaration of Helsinki (World Medical Association, 2001) and the approval of the experimental protocol was obtained from the appropriate Anglia Ruskin University Human Research Ethics Committee. All participants provided written informed consent before the experiments were conducted and after the nature and consequences of the study were explained.

Pilot experiment: staircase design

Adult participants were recruited through personal contacts. All participants wore full refractive correction (full spectacle correction with best vision sphere of -2.25D to $+0.75$D spectacle lenses) with visual acuity of at least 6/5 and normal stereo-acuity. Four of the participants (AM, JEB, KM and SL) were participants in Experiment 1, two of whom (AM and SL) did longer staircases with a greater number of reversals. Data for the method of constant stimuli generated in Experiment 1 was used for comparison with those measured with the staircase method in Experiment 2 in four adults. Six additional adult participants (AC, AG, JL, JPS, JS, and MF) had their visual acuities measured for all stimulus types with staircases bringing the total to ten adults, to compare subsequently with data obtained in children.

Main experiment

Ninety-one children aged 3 to 16 years (inclusive) took part in Experiment 2. The children were separated into four age groups: 3-4, 5-7, 8-11 and 12-16 years of age. Prior to recruitment, a sample size calculation was conducted to ensure outcomes would hold statistical meaning. A clinically significant change in acuity is considered to be 1 line on an acuity chart, or 0.1 logMAR, and the repeatability of clinical measures of visual acuity have been measured to be ± 0.1 logMAR (Klein et al., 1983; Arditi and Cagenello, 1993; Siderov and Tiu, 1999). Statistically then, using an expected effect size of 0.1 logMAR and a variability of the outcome variable measure of 0.1 logMAR (giving a standardised effect size of 1.00), a sample size of $n = 16$ should result in statistical differences arising, should they truly exist. The calculation was conducted using a two-tailed significance level (or α) of 0.05, and a power (or β) of 0.80, both of which are commonly used in clinical research studies (Stewart et al., 2006; Norgett and Siderov, 2011; Foss et al., 2013). Consequently, a minimum of 16 participants were recruited for each of the 4 age groups.

Participants were recruited through personal contacts and also advertised for through schools (i.e. school newsletters and in book bags). Participant information forms and consent forms are presented in Appendix D. Children normally did one picture/symbol test and one letter test (if they were able to name or match letters). Most of these children were 3 to 4 years of age. Efforts were made to have roughly equal numbers of participants for Kay Pictures compared to Lea Symbols and HOTV compared to Cambridge Crowded for each age. However, if a child was not able to name the optotypes on the planned test then an alternative was used where possible. Due to greater testability with the 3 year olds on the Kay Picture test than the Lea Symbols test, the number of 3 year olds who did the Kay Picture test was higher than the number that did the Lea Symbols test. Numbers of 3 to 4 year olds (shown in Table 3.2) were lower for letters. Atkinson et al. (1986) also found that crowded letters were too cognitively taxing for 3 to 4 year olds.

A Welch Allyn (Welch Allyn, New York, USA) SureSight™ auto-refractor , which is effective as a screening tool (Iuorno et al., 2004; Rowatt et al., 2007; Silverstein et al., 2009) although tends to overestimate refractive error (Donahue and Johnson, 2001; Iuorno et al., 2004; Kemper et al., 2005; Choong et al., 2006; Rowatt et al., 2007; Silverstein et al., 2009) and the magnitude of astigmatism (Harvey et al., 2009), was used. If a habitual spectacle correction was worn an over-refraction was conducted. Children were excluded from participating in the study if there was known ocular pathology, as reported by the parent. If the auto-refractor result was outside the normal limits as indicated by the referral criteria for the Welch Allyn SureSight autorefractor (WelchAllyn, 1996) then a sight test was advised. Due to the aforementioned tendency for the Welch Allyn SureSight auto-refractor to overestimate refractive error, if a sight test indicated no significant refractive error, then the results were included. If the sight test indicated significant refractive error, or the results were not reported back to the researcher then the results for that participant were excluded. All parents were advised that sight tests are free (under the NHS) for all children under the age of 16 in the United Kingdom.

Full information was given to, and consent obtained from, the accompanying parent or legal guardian (see Appendix D). In addition, information appropriate to the child's age and ability to understand was given to the child and they were asked if they wanted to take part in the experiment or not. Children who were in any way unsure were given the option of watching someone (e.g. their sibling) do the experiment first before deciding whether or not to take part.

A summary of the number of participants of each age group who completed vision tests is shown in Table 3.2. The age of participants, their auto-refraction result and it's reliability score, their habitual spectacle prescription, the order of tests done and additional notes were recorded for the children aged 3-4 years old (in Table 3.3), 5-7 years old (in Table 3.4), 8-11 years old (in Table 3.5) and 12-16 years old (in Table 3.6). Excluded participants are detailed in Table 3.7. Auto-refraction reliability scores of ≤ 4 are considered poor (WelchAllyn, 1996) and 5 is marginal. Where the reliability scores was ≤ 5 the auto-refraction was repeated and the reading with the highest reliability score was retained.

Table 3.2: *Participant numbers for all 4 tests (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowded) for all 4 age groups (3-4, 5-7, 8-11 and 12-16 years old).*

Age group	Kay Picture	Lea Symbols	HOTV	Cambridge Crowded	Total
3-4 years	12	8	4	6	30
5-7 years	13	11	7	8	38
8-11 years	7	10	8	10	37
12-16 years	10	8	9	9	36
Total	42	34	28	31	135

Table 3.3: *Participant details for participants aged 3-4 years old.*

No.	Age (y)	Eye	Auto-refractor (reliability)	Test 1	Test 2	Notes
1	2.92	R	$+0.25/-0.25 \times 76$ (9)	Lea	CC	
2	3.00	R	$+2.00/-0.50 \times 15$ (6)	Lea		[1]
3	3.00	R	$+1.00/-1.00 \times 123$ (6)	Kay		[2]
4	3.00	R	$+3.00/-0.25 \times 84$ (3)	HOTV	CC	[3]
5	3.08	R	$+0.50/-1.25 \times 178$ (8)	Lea		[4]
6	3.17	L	$+1.25/-0.75 \times 89$ (6)	HOTV	CC	
7	3.25	R	$+1.50/-0.25 \times 104$ (7)	Kay		
8	3.25	R	$+1.50/-0.50 \times 80$ (9)	Lea		
9	3.67	R	$+1.00/-0.75 \times 170$ (7)	Kay		
10	3.67	R	$+1.00/-0.75 \times 170$ (7)	Kay		
11	3.67	L	$+1.75/-0.25 \times 15$ (6)	Kay		
12	3.83	R	$+1.50/-0.25 \times 15$ (6)	Kay		
13	3.92	R	$+1.25/-0.25 \times 122$ (8)	Kay		
14	4.00	L	$+1.25/-0.50 \times 126$ (9)	Lea		
15	4.00	R	$+1.00/-0.25 \times 175$ (8)	Lea		
16	4.08	R	$+1.50/-1.00 \times 90$ (9)	Kay		[5]
17	4.42	L	$+1.25/-0.25 \times 2$ (5)	Kay		
18	4.42	R	$+0.75/-0.25 \times 164$ (8)	Lea		
19	4.58	L	$+0.75/-0.25 \times 8$ (7)	Kay	CC	
20	4.58	L	$+3.50/-0.25 \times 15$ (8)	HOTV	CC	[6]
21	4.58	L	$+2.00/-0.50 \times 71$ (6)	CC	HOTV	
22	4.75	R	$+1.25/-0.50 \times 18$ (5)	Kay		
23	4.92	R	$+0.75/-0.25 \times 16$ (7)	Kay		[7]
24	4.92	L	$+0.75/-0.25 \times 87$ (8)	Lea		

[1] Sight test showed <1.00D refractive error, no refractive correction was considered necessary.
[2] Sight test showed <0.50DC of astigmatism.
[3] Sight test showed <1.00D refractive error, no refractive correction was considered necessary.
[4] Sight test showed less than 0.50DC of astigmatism, refractive correction of $+0.75$DS given.
[5] Sight test showed <0.50DC of astigmatism.
[6] Dizygotic twins. Sight tests on both children showed no significant refractive error and no refractive correction was considered necessary.
[7] Monozygotic twins

Table 3.4: *Participant details for participants aged 5-7 years old.*

No.	Age (y)	Eye	Auto-refractor (reliability)	Test 1	Test 2	Notes
25	5.08	R	$+0.75/-0.50 \times 99$ (9)	Lea	CC	
26	5.17	L	$+0.50/-0.50 \times 2$ (7)	Lea		
27	5.25	R	$+2.25/-0.50 \times 6$ (7)	HOTV	CC	[8]
28	5.42	R	$-0.75/-0.50 \times 65$ (7)	Kay		
29	5.58	L	$+1.25/-0.75 \times 63$ (7)	Lea	Kay	
30	5.58	L	$+1.50/-0.25 \times 54$ (9)	Kay		
31	5.75	L	$+1.75/-0.25 \times 114$ (7)	HOTV	CC	
32	6.00	L	$+1.75/-0.75 \times 13$ (8)	Lea		
33	6.58	L	$+1.50/-0.50 \times 23$ (6)	HOTV	CC	
34	6.75	R	$+1.25/-0.25 \times 18$ (7)	Kay		[9]
		L	$+1.75/-0.75 \times 167$ (8)			
35	6.75	L	$+1.25/-0.25 \times 103$ (9)	HOTV	CC	
36	6.92	L	$+1.00/-0.50 \times 162$ (6)	Kay		
37	7.00	R	$-2.00/-0.25 \times 8$ (8)	Kay		[10]
38	7.00	R	$-2.00/-0.25 \times 117$ (5)	Lea		
39	7.08	R	$+1.25/-0.25 \times 89$ (8)	Kay		
40	7.08	R	$+1.75/-0.75 \times 93$ (7)	Kay		
41	7.17	L	$+1.50/-0.50 \times 77$ (8)	Lea		
42	7.17	L	$+1.75/-0.50 \times 98$ (4)	Lea	Kay	
43	7.33	R	$-2.25/-0.25 \times 67$ (7)	Lea		[11]
44	7.42	R	$+0.25$DS (9)	Lea	CC	
45	7.50	L	$+1.50/-0.25 \times 165$ (7)	Kay		
46	7.58	R	$-0.50/-0.25 \times 78$ (4)	Kay		
47	7.67	L	$+1.00/-0.50 \times 162$ (4)	Lea		
48	7.75	R	$-0.25/-0.25 \times 105$ (8)	CC	HOTV	
49	7.83	R	$-1.00/-0.50 \times 87$ (6)	HOTV	CC	[12]
50	7.92	R	$-0.25/-0.50 \times 7$ (6)	Lea		
51	7.92	L	$-2.00/-0.50 \times 21$ (7)	Kay		[13]
52	7.92	L	$+1.50/-0.50 \times 96$ (5)	Kay	HOTV	

[8] Sight test showed <1.00D refractive error, no refractive correction was considered necessary.
[9] Binocular. Participant was happy to take part but would not tolerate having either eye covered.
[10] Monozygotic twins. Sight tests on both children showed no significant refractive error and no refractive correction was considered necessary.
[11] Sight test showed <1.00D refractive error, no refractive correction was considered necessary.
[12] Sight test showed <1.00D refractive error, no refractive correction was considered necessary.
[13] Habitual Rx (-1.00DS) worn.

Table 3.5: *Participant details for participants aged 8-11 years old.*

No.	Age (y)	Eye	Auto-refractor (reliability)	Test 1	Test 2	Notes
53	8.08	L	$+0.75/-0.25 \times 53$ (7)	Lea	HOTV	
54	8.58	L	$-1.50/-0.25 \times 82$ (5)	CC	Kay	[14,15]
55	8.58	R	$-0.50/-0.75 \times 72$ (6)	CC	Lea	[15]
56	8.83	L	$-1.25/-0.25 \times 91$ (6)	CC	HOTV	[16]
57	9.17	R	$+1.00/-0.25 \times 170$ (9)	HOTV	Kay	
58	9.33	R	$+1.25/-0.50 \times 163$ (5)	Lea	CC	
59	9.92	L	$-0.50/-0.25 \times 31$ (7)	Kay	HOTV	
60	10.33	L	$-1.75/-0.25 \times 87$ (9)	Lea	HOTV	[17]
61	10.58	R	$-0.50/-0.25 \times 46$ (8)	Kay	CC	[18]
62	10.67	L	$-1.00/-0.50 \times 16$ (7)	CC	Lea	[19]
63	10.83	L	$+0.75/-0.25 \times 176$ (7)	HOTV		
64	10.92	R	-0.75DS (8)	Kay	HOTV	
65	11.00	R	$-0.50/-0.25 \times 46$ (8)	CC	Kay	
66	11.08	L	$-0.25/-1.25 \times 93$ (3)	Kay	CC	[20]
67	11.58	L	$+0.25/-0.25 \times 6$ (8)	Lea	CC	
68	11.67	R	$-0.50/-0.25 \times 80$ (6)	HOTV	Lea	[21]
69	11.75	L	$-0.25/-0.25 \times 72$ (6)	Lea	CC	
70	11.92	R	$-0.50/-0.50 \times 81$ (8)	Lea		
71	11.92	R	$0.00/-0.25 \times 35$ (8)	Lea		[22]
		L	$-0.75/-0.25 \times 5$ (4)			

[14] Sight test showed <0.50D refractive error.
[15] Dizygotic twins.
[16] Sight test showed <1.00D refractive error.
[17] Sight test showed -0.75DS refractive error.
[18] Sight test showed 0.00DS.
[19] Sight test showed <0.50D refractive error.
[20] Sight test showed <1.00D refractive error.
[21] Habitual Rx: -0.50DS.
[22] Refused to have either eye covered. Tested binocularly.

Table 3.6: *Participant details for participants aged 12-16 years old.*

No.	Age (y)	Eye	Auto-refractor (reliability)	Test 1	Test 2	Notes
72	12.00	R	$-0.75/-0.25 \times 12$ (7)	Lea	HOTV	
73	12.08	L	$-1.75/-1.25 \times 180$ (5)	HOTV	Kay	[23]
74	12.25	L	$-1.75/-0.50 \times 164$ (7)	Kay	CC	[24]
75	12.42	R	$-0.25/-0.25 \times 126$ (8)	Lea	HOTV	
76	12.67	R	$0.00/-0.25 \times 65$ (7)	Lea	CC	
77	12.75	L	$-0.50/-0.25 \times 85$ (6)	Kay	CC	[25]
78	12.75	R	$0.00/-0.75 \times 11$ (7)	Lea	CC	[26]
79	12.92	L	$-0.75/-0.50 \times 5$ (7)	CC	Kay	[27]
80	13.50	L	$-0.75/-0.25 \times 25$ (5)	Kay	HOTV	
81	13.58	L	$-0.25/-0.25 \times 6$ (6)	Lea	CC	
82	13.83	L	$-0.75/-0.25 \times 58$ (8)	HOTV		
83	14.25	L	$-0.25/-0.25 \times 58$ (8)	HOTV	Kay	
84	14.58	R	$-1.00/-0.25 \times 38$ (5)	Lea	HOTV	[28]
85	14.67	L	$+0.75/-0.75 \times 38$ (4)	Kay	CC	
86	15.00	R	$-1.75/-0.25 \times 35$ (8)	CC	Lea	[29]
87	15.33	R	$-1.75/-0.50 \times 42$ (4)	Kay	HOTV	[30]
88	15.75	R	$+0.50/-0.50 \times 87$ (8)	Lea	HOTV	
89	16.50	R	$-0.25/-0.50 \times 25$ (7)	Kay	CC	[31]

[23] Sight test showed <1.00D refractive error, no refractive correction was considered necessary.
[24] Sight test showed <1.00D refractive error, no refractive correction was considered necessary.
[25] Habitual rx was left at home so full refraction was obtained and used ($-3.00/-0.25 \times 120$).
[26] Habitual Rx: -0.50DS.
[27] Sight test showed sphere and cyl < 0.50D.
[28] Sight test showed <1.00D refractive error, no refractive correction was considered necessary.
[29] Refractive error of -0.50DS.
[30] Sight test showed <1.00D refractive error, no refractive correction was considered necessary.
[31] Habitual Rx: -0.75DS.

Table 3.7: *Details of excluded participants.*

No.	Age (y)	Eye	Auto-refractor (reliability)	Test 1	Test 2	Notes
90	3.17	L	$+3.50/-0.25 \times 141$ (6)	Kay		[32]
91	14.25	R L	$-1.00/-0.50 \times 137$ (4) $+0.50/-0.75 \times 17$ (5)	Lea	CCC	[33]

[32] No habitual prescription - has never had a sight test. Unable to match very large picture (1.3 logMAR) with matching card.
[33] Anisometropic amblyopia (left eye).

3.3.3 Stimuli

L, LM and CM versions of Kay Pictures, Lea Symbols, HOTV and Cambridge Crowded tests, were modified in the same ways as in Experiment 1 (see Chapter 2). Optotypes (see Figure 3.7) were displayed without crowding or contour interaction features (referred to as the isolated condition) and with a target-flanker separation distance of 1 stroke width, which was determined in Experiment 1 to be the optimal placement. Although this was decided based on data obtained with normal adults, the extent of contour interaction and crowding is larger in children up to approximately 10 years of age and then becomes adult like (Semenov et al., 2000; Bondarko and Semenov, 2005). Contour interaction should therefore still occur at 1 stroke width separation.

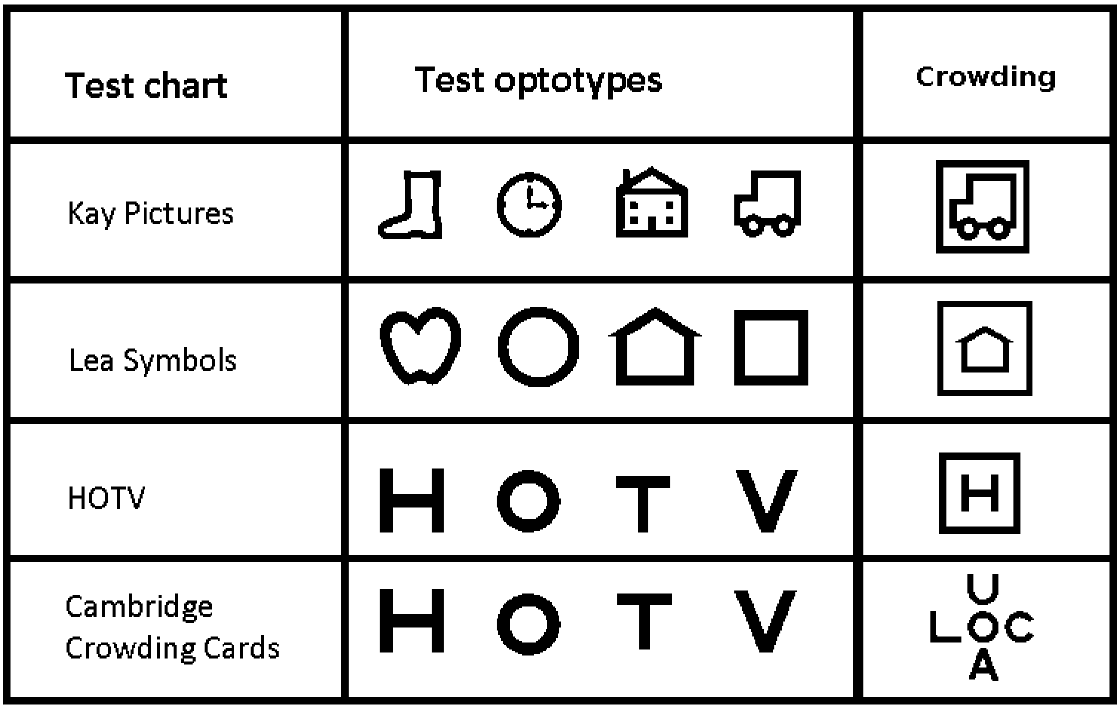


Figure 3.7: *The four optotypes used for each test are shown with an example of a "crowded" optotype on the right hand side.*

3.3.4 Procedure

From the results of the pilot experiment, for the main experiment a 2-down, 1-up staircase procedure was selected for two reasons: the requirement of two correct guesses before reducing the optotype size makes it less likely to occur by chance (probability of 6.25%); but the staircase will not be unnecessarily lengthened by requiring too many correct answers before a reduction in the optotype size. This is in line with previous studies (see Table 3.1). It was decided that the staircase should terminate after 6 reversals, with the initial 2 reversal points omitted when averaging reversal points to calculate the threshold. With the youngest children, the staircase was terminated after 4 reversals if attention level wandered or they were reluctant to guess. Catch trials using very large letters or symbols about 0.3 logMAR above the expected threshold were used every six presentations to motivate the child and to minimise the ability to predict target sequencing. Responses to catch trials were monitored but not used in calculations of visual acuity. Incorrect responses to catch trials were recorded in the results file and caused the catch trial size to increase to the largest that could be displayed.

All participants were given the matching card (shown in Appendix C) and had the option of either pointing to or saying the optotype they saw. The children named the optotypes on the matching card before starting. Visual acuities were estimated for isolated and crowded (at 1 stroke width separation) individual optotypes with standard luminance (L), luminance modulated (LM) and contrast modulated (CM) stimuli. Two tests (symbols and letters) were used unless the child was unwilling or unable to match letters (predominantly younger children) in which case they only did one test (a picture or symbol test).

3.3.5 Analysis

Pilot experiment

Visual acuity was calculated by averaging different numbers of reversal points. On a staircase without any false-positives or false-negatives which started from a supra-threshold point, the staircase would descend until just below the threshold. Each reversal point would then be on either side of the threshold alternately. Any false-positives or false-negatives would cause the staircase to deviate from this path. An investigation of the effect of false-positives or false-negatives on the calculated threshold was carried out (see Section 3.4)

Main experiment

Visual acuity was estimated for each condition (symbols and/or letters; isolated or flanked; L, LM or CM stimuli) by calculating the mean, standard deviation and standard error of the reversal points (after the first two reversals were ignored). A small number of children repeated the experiments. For these children visual acuity estimates were compared to assess test-retest repeatability. The magnitude of contour interaction and crowding was calculated by subtracting the "crowded" logMAR acuity from the isolated logMAR acuity. Statistical analysis was done using a mixed methods repeated measures ANOVA with Huynh-Felt correction for violations of sphericity.

To determine the age at which visual acuities became adult-like, visual acuities (in logMAR) for adults and children were plotted against log age (in log years). The data were subsequently fit with a two-line (power-function) model with an initial negative slope, indicating a decrease (or improvement) in visual acuity, intersecting with a subsequent line with a slope of 0, indicating no change in visual acuity. The steepness of the initial slope was also analysed to obtain information on the rate of change across the ages where development is occurring. This is an approach used in other similar research (for example: Sukumar and Waugh, 2007; Levi and Carney, 2009; Martelli et al., 2009; Coates et al., 2013).

Results were analysed by directly comparing visual acuities for standard luminance (L) and luminance-modulated (LM) conditions, and separately comparing visual acuities for luminance-modulated (LM) and contrast-modulated (CM) conditions. The standard luminance (L) condition consists of black optotypes being presented on a white background similar to the standard clinical setup. The luminance-modulated (LM) condition is similar to the luminance-defined (L) condition but with the addition of dynamic noise across the stimulus. The effect of noise *per se* can be examined by comparing the data obtained for the L and LM conditions. The contrast-modulated (CM) condition is a new type of optotype created by differences in contrast between the optotype and the background. The background dynamic noise is the same for optotypes created by the LM and CM conditions. By comparing LM and CM visual acuity, the effects of the specific noise effects is negated.

Statistical analyses of the data were performed using a repeated measures Analysis of Variance (ANOVA) with a Huynh-Feldt correction for the violation of sphericity assumption. When appropriate, post hoc analyses were carried out with a Tukey HSD test.

3.4 Results

Pilot Experiment: Staircase design

A supra-threshold starting point has been used in similar research (see Table 3.1), particularly when using young children, as starting with optotypes that cannot be recognised or are below threshold can be particularly frustrating for young children. A step size of 0.1 logMAR (as was used with the Method of Constant Stimuli) resulted in staircases taking on average 1.47 ± 0.71 minutes of time for adults. This was considered to be sufficiently quick, rather than using an adaptive staircase starting with a larger step size that reduced as it neared threshold.

Longer staircases (more than 16 reversal points) showed that early false negative responses (before the first true reversal point) caused the first two reversal points to be far more different from other reversal points than if a false positive or false negative occurred anywhere after the first true reversal point (see Figure 3.8). The decision was made to therefore ignore the first two reversal points, which is common practice in other similar research studies (see Table 3.1). Calculations of visual acuity in adults were very similar regardless of how many reversal points were averaged if the initial two reversals were ignored.

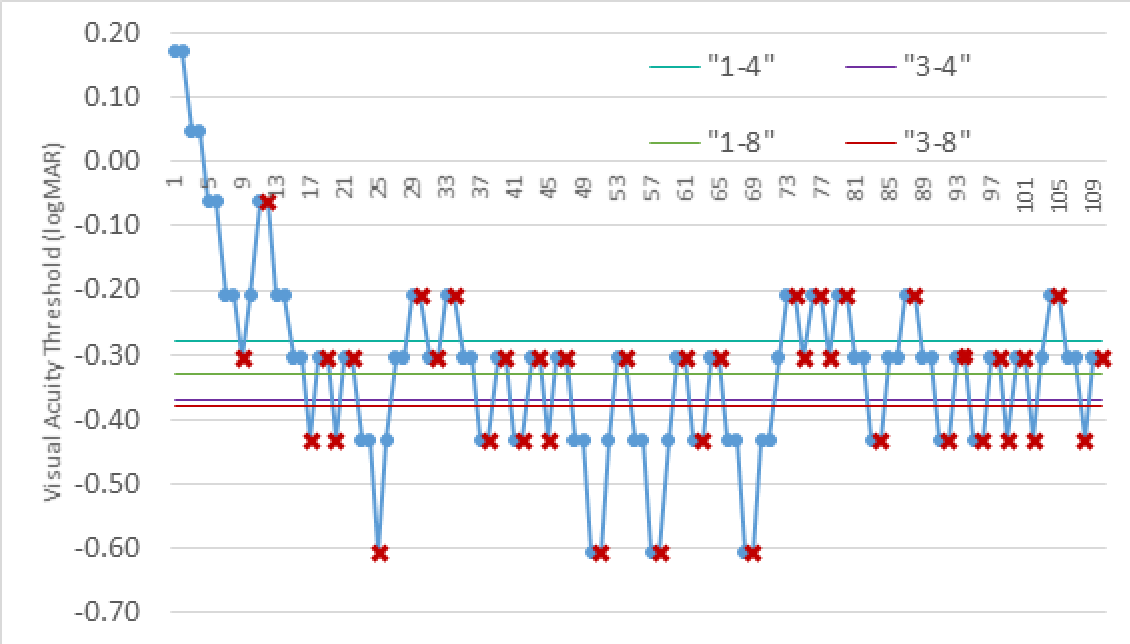


Figure 3.8: *An example staircase with 40 reversal points, showing the reversal points as red crosses and the visual acuity thresholds calculated using reversal points: 1-4, 1-8, 3-4 and 3-8. All "catch trials" (every sixth trial) have been removed on from the graph for the purposes of clarity.*

Results from the staircase method compared to the method of constant stimuli

In adult participants, visual acuity thresholds were on average 0.048 ± 0.012 logMAR higher (worse) when obtained using the method of constant stimuli than when calculated with the staircase method (see Figure 3.9). These differences in acuity estimates across method are smaller than visual acuity repeatability measurements (of about ± 0.1 logMAR) using a standard visual acuity chart in adults (Klein et al., 1983; Arditi and Cagenello, 1993; Siderov and Tiu, 1999).

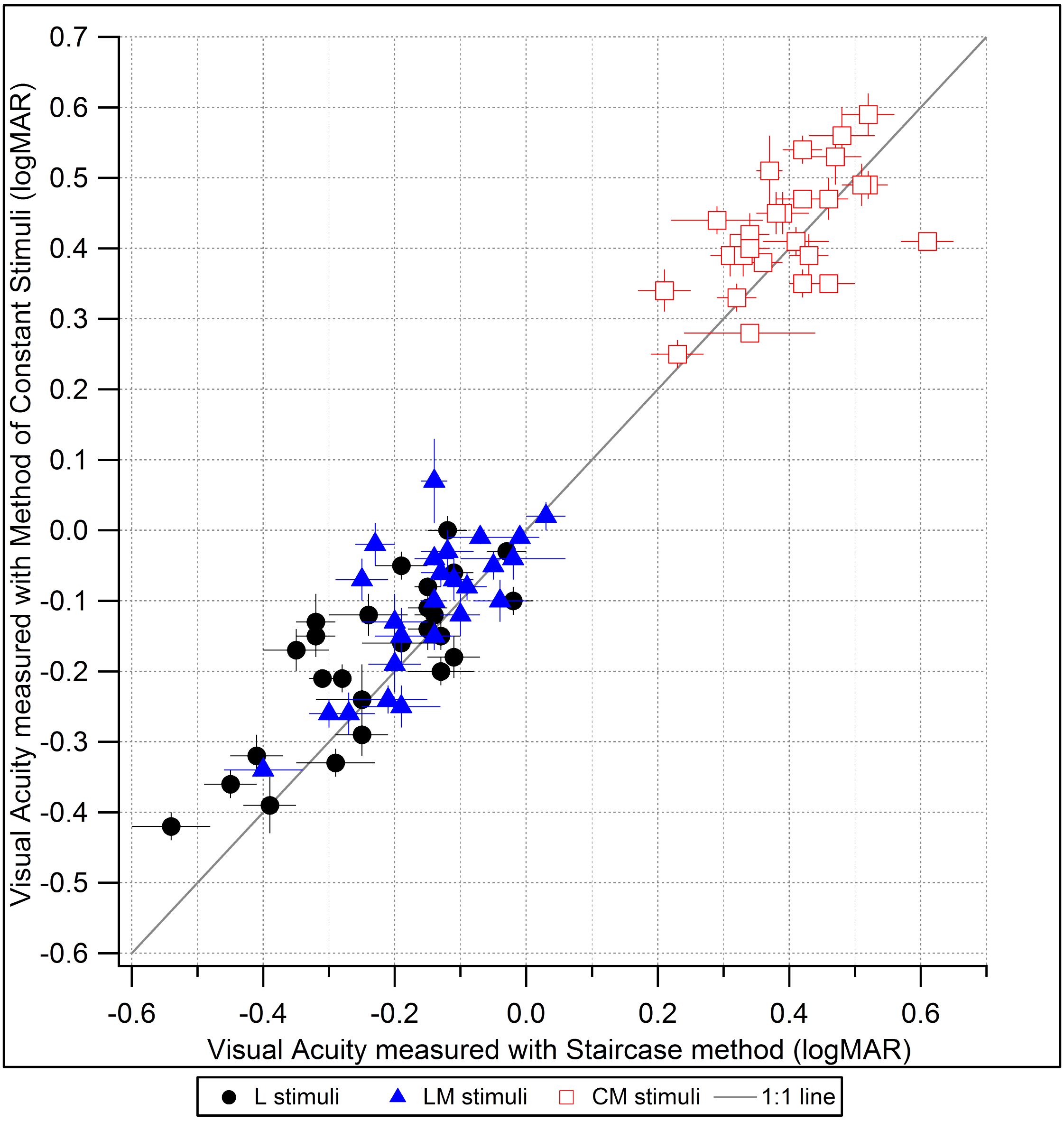


Figure 3.9: *A scatter graph plotting the visual acuity thresholds measured and calculated using the staircase method (x axis) and the method of constant stimuli (y axis) for L, LM and CM versions of the all 4 tests (Kay Pictures, Lea Symbols, HOTV and Cambridge Crowded) with and without contour interaction/crowding features.*

3.4.1 Main Experiment: Development of visual acuity with L, LM and CM stimuli

Visual acuity depended on the test used to measure it (Kay Pictures, Lea Symbols, HOTV or Cambridge Crowded), the stimulus condition (L, LM or CM) and the separation of crowding and contour interaction features.

When is adult-like acuity obtained with isolated optotypes?

Visual acuities for isolated optotypes (i.e. those measured without any crowding or contour interaction features) for children of different ages are shown in Figure 3.10. The age at which visual acuity becomes adult-like ("critical age") was assessed by finding the intersection between two power functions (straight lines on log-log axes). Visual acuities for isolated optotypes, as can be seen in Figure 3.10, become adult-like later (see Table 3.8) for CM optotypes (at 9.7 ± 1.2 years) than for L and LM optotypes (at 8.0 ± 1.1 and 7.9 ± 1.1 years, respectively). The slope of the initial line in the 2-line fit (showing the rate of improvement in visual acuity with age) is also shallower with CM stimuli (-0.56 ± 0.08) than for L (-0.82 ± 0.10) and LM (-0.69 ± 0.11) stimuli, indicating a slower rate of development for isolated CM stimuli.

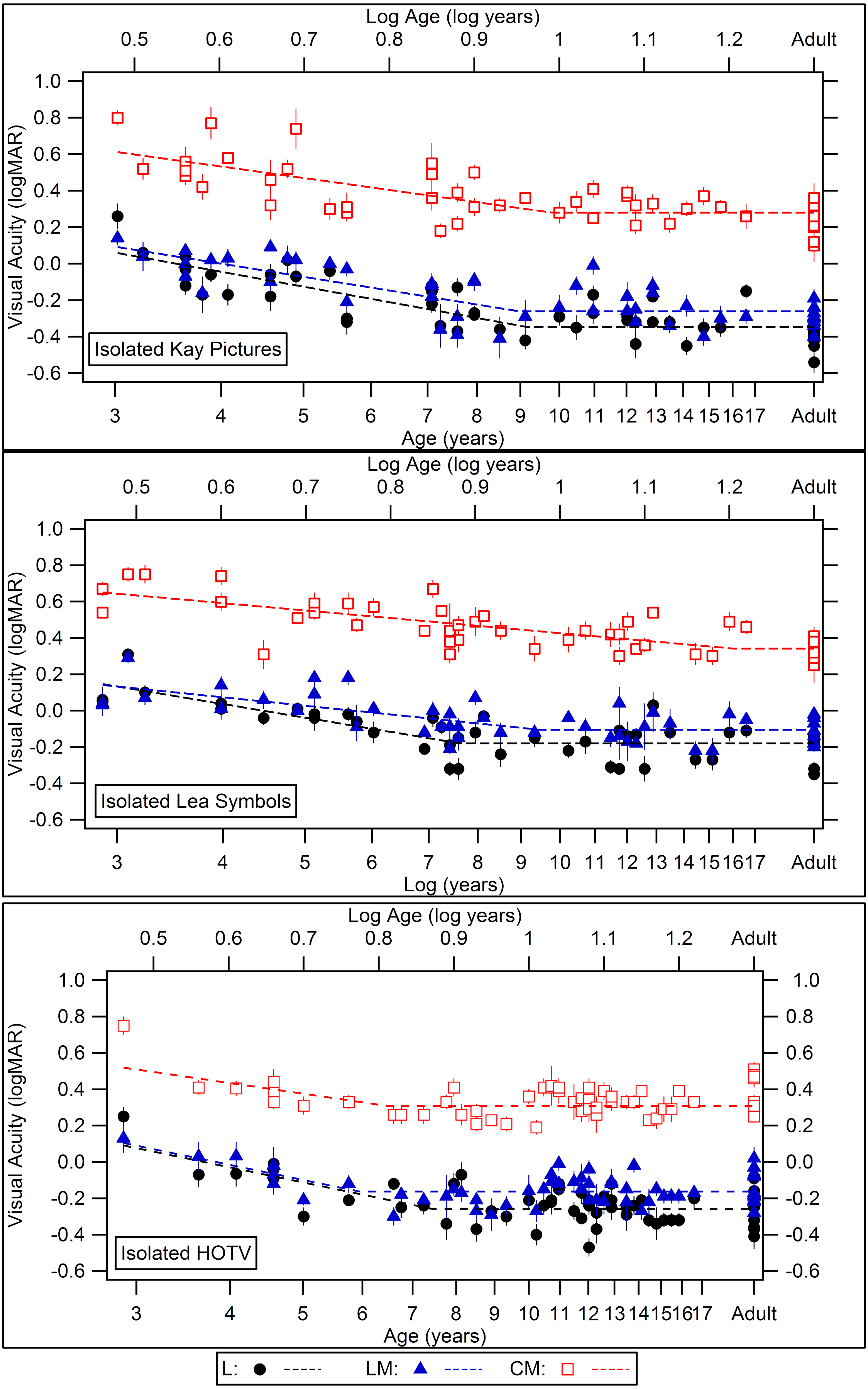


Figure 3.10: *Visual acuity estimates of children aged 3-16 years and adults measured using the staircase method with isolated Kay Picture, Lea Symbols and HOTV optotypes with a two-line fit to the data. Error bars indicate ±1 SE.*

Table 3.8: *The initial line slope, intersection point and adult-like acuity for a 2-line-fit to L, LM and CM Kay Pictures, Lea Symbols and HOTV isolated optotypes.*

Test		Initial slope	Adult VA (logMAR)	Critical age (log years)	Age (years)
Kay Pictures	L	-0.84 ± 0.14	-0.35 ± 0.02	0.96 ± 0.05	9.2 ± 1.1
	LM	-0.74 ± 0.14	-0.26 ± 0.02	0.95 ± 0.06	9.0 ± 1.1
	CM	-0.65 ± 0.15	0.28 ± 0.02	0.99 ± 0.08	9.8 ± 1.2
Lea Symbols	L	-0.77 ± 0.14	-0.18 ± 0.02	0.88 ± 0.04	7.6 ± 1.1
	LM	-0.48 ± 0.11	-0.11 ± 0.02	0.97 ± 0.07	9.4 ± 1.2
	CM	-0.44 ± 0.08	0.35 ± 0.02	1.2 ± 0.09	14 ± 1
HOTV	L	-0.85 ± 0.24	-0.26 ± 0.01	0.87 ± 0.06	7.4 ± 1.2
	LM	-0.85 ± 0.31	-0.16 ± 0.01	0.77 ± 0.06	5.9 ± 1.2
	CM	-0.60 ± 0.19	0.31 ± 0.00	0.81 ± 0.06	6.5 ± 1.1
Average	L	-0.82 ± 0.10	-0.26 ± 0.02	0.90 ± 0.05	8.0 ± 1.1
	LM	-0.69 ± 0.11	-0.18 ± 0.02	0.90 ± 0.06	7.9 ± 1.2
	CM	-0.56 ± 0.08	0.31 ± 0.02	0.99 ± 0.07	9.7 ± 1.2

The data from Figure 3.10 are also grouped according to age-groups, which are statistically compared using repeated measures analyses of variance (ANOVA tables available in Tables 3.9 and 3.10). Tukey post-hoc comparisons determined whether or not visual acuity for different child age groups were different or not from the adult group.

For L and CM stimuli, child visual acuity is significantly different from adult acuity for 3-4 year olds and 5-7 year olds (see Figures 3.11 and 3.12), although for LM stimuli only the 3-4 year old age group reaches significance.

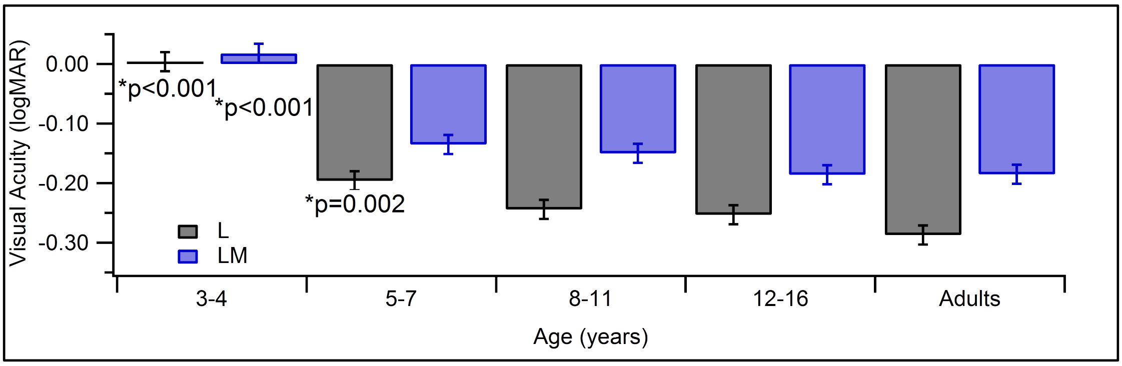


Figure 3.11: *Visual acuities with L and LM optotypes with 3-4, 5-7, 8-11 and 12-16 year olds and adults. P values show significant differences from adult acuities.*

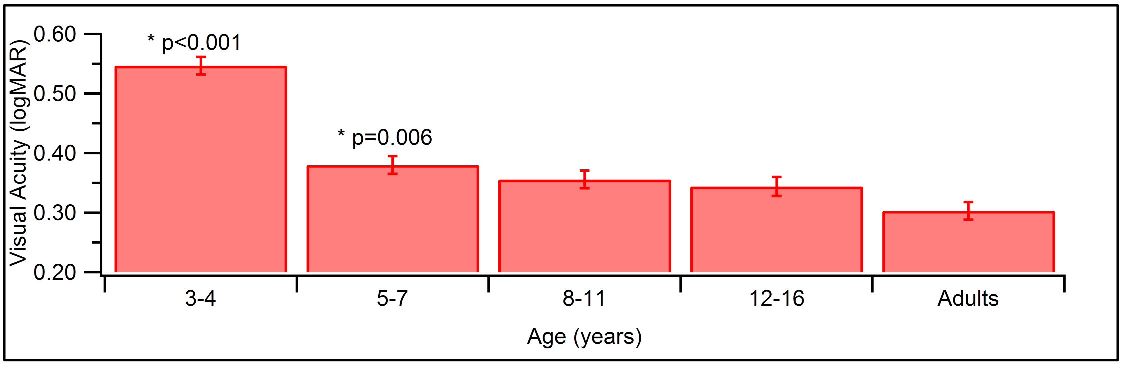


Figure 3.12: *Visual acuities with CM optotypes with 3-4, 5-7, 8-11 and 12-16 year olds and adults. P values show significant differences from adult acuities.*

Visual acuity for isolated optotypes in children for different stimulus types (L, LM and CM)

Visual acuities for L and LM isolated optotypes for children of different ages are shown in Figure 3.11. Overall, acuities measured with LM optotypes were significantly higher (worse) than with L optotypes [F(1.0,55)=110, p<0.001] and this difference between L and LM acuities increases with age [F(4.0,55)=5.7, p=0.001] from 0.015 ± 0.012 logMAR with 3-4 year olds to 0.10 ± 0.01 logMAR with adults.

Acuities measured with CM optotypes were significantly higher (worse) than with LM optotypes [F(1.0,54)=5600, p<0.001] and this was consistent across age groups [F(4.0,54)=1.7, p=0.17]. Acuities were 0.51 ± 0.01 logMAR worse ($3.2\times$ larger) when measured with contrast modulated (CM, red squares) optotypes than with luminance modulated (LM, blue triangles) optotypes.

The ANOVA results that relate to these findings is provided in Tables 3.9 and 3.10. Outcomes related to significant differences between test (Kay Pictures, Lea Symbols, HOTV) are highlighted in Section 3.4.3.

Table 3.9: *A 3 (test) × 2 (stimulus) repeated measures ANOVA with isolated L and LM Kay Pictures, Lea Symbols and HOTV optotypes with 1 between subject variable (age).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Age	**2.9**	**4.0**	**0.72**	**47**	**<0.001**	**0.77**
Error	0.84	55	0.015			
Test	**1.0**	**2.0**	**0.51**	**75**	**<0.001**	**0.58**
Test*Age	**0.22**	**8.0**	**0.027**	**3.9**	**<0.001**	**0.22**
Error	0.76	110	0.007			
Stimulus	**0.41**	**1.0**	**0.41**	**110**	**<0.001**	**0.66**
Stimulus*Age	**0.086**	**4.0**	**0.002**	**5.7**	**0.001**	**0.29**
Error	0.21	55	0.004			
Test*Stimulus	0.003	2.0	0.002	0.53	0.59	0.010
Test*Stimulus*Age	**0.061**	**8.0**	**0.008**	**2.6**	**0.012**	**0.16**
Error	0.32	110	0.003			

Table 3.10: *A 3 (test) × 2 (stimulus) repeated measures ANOVA with isolated LM and CM Kay Pictures, Lea Symbols and HOTV optotypes with 1 between subject variable (age).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Age	**0.96**	**4.0**	**0.24**	**46**	**<0.001**	**0.77**
Error	0.29	55	0.005			
Test	**0.89**	**1.9**	**0.46**	**78**	**<0.001**	**0.59**
Test*Age	**0.20**	**7.7**	**0.025**	**4.3**	**<0.001**	**0.24**
Error	0.63	110	0.006			
Stimulus	**0.36**	**1.0**	**0.36**	**120**	**<0.001**	**0.69**
Stimulus*Age	**0.055**	**4.0**	**0.014**	**4.7**	**0.002**	**0.26**
Error	0.16	55	0.003			
Test*Stimulus	**0.025**	**2.0**	**0.012**	**4.1**	**0.020**	**0.069**
Test*Stimulus*Age	0.036	8.0	0.005	1.5	0.17	0.097
Error	0.33	110	0.003			

When is adult-like acuity obtained with optotypes surrounded by a box (contour interaction)?

Visual acuities for optotypes surrounded by a box for children of different ages are shown in Figure 3.13. The age at which visual acuity becomes adult-like was assessed by finding the intersection between two power functions (straight lines on log-log axes). The age at which visual acuity is adult-like was on average 0.34 ± 0.20 years later than with isolated optotypes based on a two-line fits to the data as shown in Figures 3.10 and 3.13. Acuities became adult-like later (see Table 3.11) for CM optotypes (9.9 years old) than for L and LM optotypes (8.1 and 8.7 years old, respectively). As with isolated optotypes, the slope of the initial line in the 2-line fit is shallower for CM optotypes (-0.55 ± 0.10) than for L and LM optotypes (-0.76 ± 0.14 and -0.68 ± 0.08, respectively). Visual acuities grouped by age are shown for L and LM (Figure 3.14) and CM (Figure 3.15) optotypes. For L and LM stimuli, child visual acuity is significantly different from adult acuity for 3-4, 5-7 and 8-11 year old age groups (see Figure 3.14), although for CM stimuli only the 3-4 and 5-7 year old age groups reach significance.

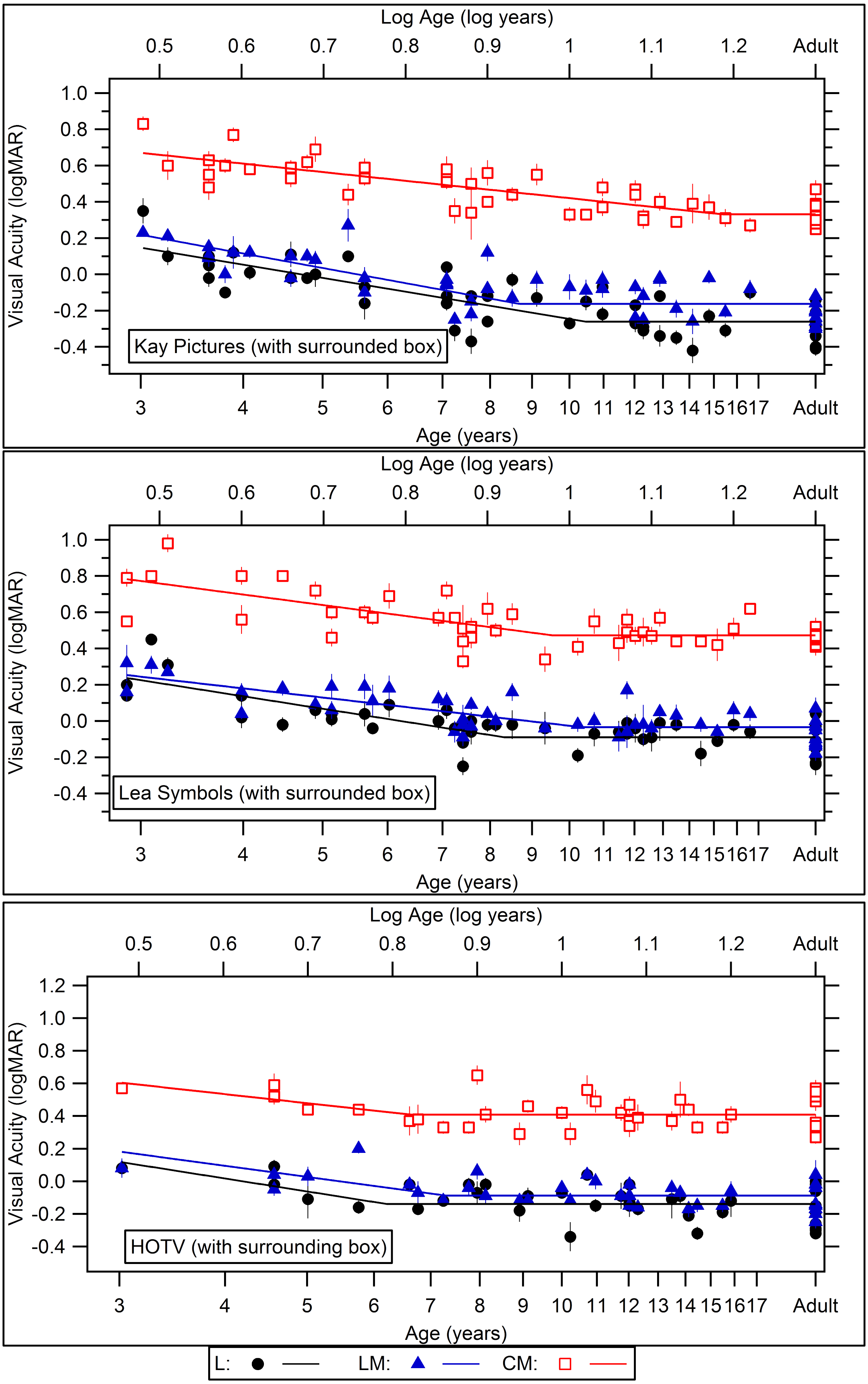


Figure 3.13: *Visual acuity estimates of children aged 3-16 years and adults measured using the staircase method with Kay Picture, Lea Symbols and HOTV optotypes surrounded by a box (1 stroke width target-flanker separation) with a two-line fit to the data. Error bars indicate ±1 SE.*

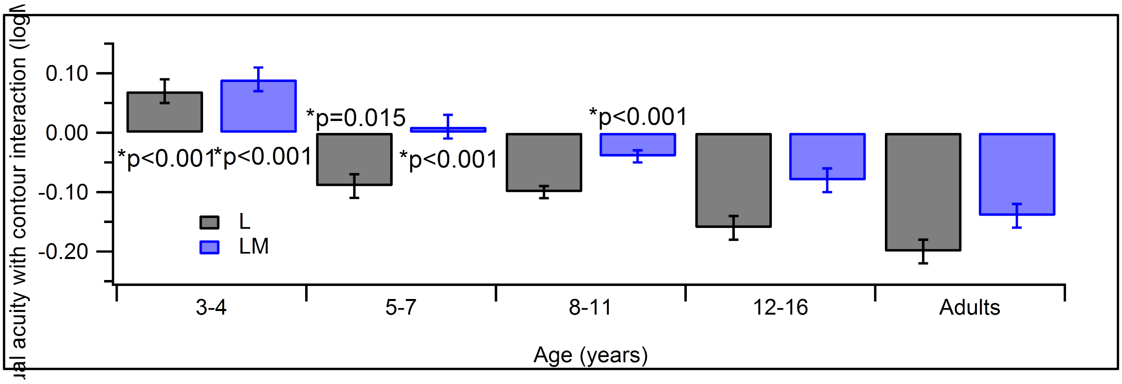


Figure 3.14: *Visual acuities with L and LM optotypes surrounded by a box with 3-4, 5-7, 8-11 and 12-16 year olds and adults. P values show significant differences from adult acuities.*

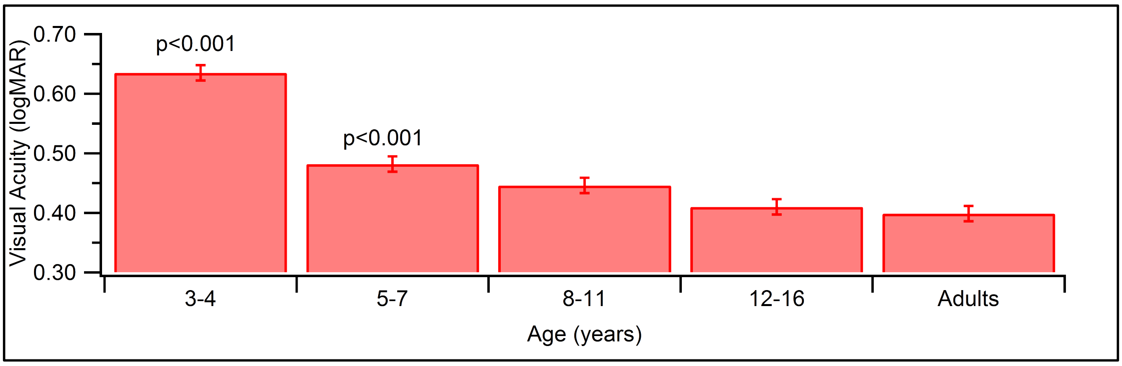


Figure 3.15: *Visual acuities with CM optotypes surrounded by a box with 3-4, 5-7, 8-11 and 12-16 year olds and adults. P values show significant differences from adult acuities.*

Table 3.11: *The initial line slope, intersection point and adult-like acuity for a 2-line-fit to L, LM and CM Kay Pictures, Lea Symbols and HOTV optotypes surrounded by a box.*

Test		Initial slope	Adult VA (logMAR)	Critical age (log years)	Age (years)
Kay Pictures	L	-0.75 ± 0.13	-0.26 ± 0.02	1.0 ± 0.1	10 ± 1
	LM	-0.83 ± 0.05	-0.16 ± 0.01	0.94 ± 0.02	8.7 ± 1.0
	CM	-0.48 ± 0.06	0.33 ± 0.02	1.2 ± 0.1	15 ± 1
Lea Symbols	L	-0.71 ± 0.12	-0.09 ± 0.02	0.92 ± 0.05	8.3 ± 1.1
	LM	-0.52 ± 0.10	-0.03 ± 0.02	1.0 ± 0.1	10 ± 1
	CM	-0.60 ± 0.12	0.47 ± 0.02	0.98 ± 0.06	9.5 ± 1.2
HOTV	L	-0.82 ± 0.48	-0.14 ± 0.02	0.79 ± 0.10	6.2 ± 1.3
	LM	-0.70 ± 0.26	-0.09 ± 0.02	0.86 ± 0.07	7.3 ± 1.2
	CM	-0.57 ± 0.35	0.41 ± 0.02	0.82 ± 0.11	6.6 ± 1.3
Average	L	-0.76 ± 0.14	-0.16 ± 0.02	0.91 ± 0.07	8.1 ± 1.2
	LM	-0.68 ± 0.08	-0.09 ± 0.01	0.94 ± 0.05	8.7 ± 1.1
	CM	-0.55 ± 0.10	0.40 ± 0.02	0.99 ± 0.08	9.9 ± 1.2

Visual acuity for optotypes with contour interaction in children in children for different stimulus types (L, LM, CM)

Visual acuities for children of different ages measured with optotypes surrounded by a box are shown in Figures 3.14 and 3.15. Overall, acuities were significantly worse with LM than L stimuli [F(1.0,55)=120, p<0.001]. As with isolated optotype acuity, the difference between L and LM acuities increased with age [F(4.0,55)=4.7, p=0.002] from a 0.018 ± 0.014 logMAR difference with 3-4 year olds to a 0.062 ± 0.014 logMAR difference with adults.

Visual acuities were significantly higher with CM than LM optotypes [F(1.0,55)=8800, p<0.001], but the difference was significantly affected by age [F(4.0,55)=6.4, p<0.001]. There was no consistent trend across age groups.

Table 3.12: *A 3 (test) × 2 (stimulus) repeated measures ANOVA for L and LM Kay Pictures, Lea Symbols and HOTV optotypes surrounded by a box with 1 between subject variable (age).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Age	**2.9**	**4.0**	**0.72**	**46**	**<0.001**	**0.77**
Error	0.87	55	0.016			
Test	**0.89**	**1.9**	**0.46**	**78**	**<0.001**	**0.59**
Test*Age	**0.20**	**7.7**	**0.025**	**4.3**	**<0.001**	**0.24**
Error	0.63	110	0.006			
Stimulus	**0.36**	**1.0**	**0.36**	**120**	**<0.001**	**0.69**
Stimulus*Age	**0.055**	**4.0**	**0.014**	**4.7**	**0.002**	**0.26**
Error	0.16	55	0.003			
Test*Stimulus	**0.025**	**2.0**	**0.012**	**4.1**	**0.020**	**0.069**
Test*Stimulus*Age	0.036	8.0	0.005	1.5	0.17	0.097
Error	0.33	110	0.003			

Table 3.13: *A 3 (test) × 2 (stimulus) repeated measures ANOVA for LM and CM Kay Pictures, Lea Symbols and HOTV optotypes surrounded by a box with 1 between subject variable (age).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Age	**2.4**	**4.0**	**0.61**	**51**	**<0.001**	**0.79**
Error	0.66	55	0.012			
Test	**0.85**	**2.0**	**0.42**	**69**	**<0.001**	**0.56**
Test*Age	**0.20**	**8.0**	**0.025**	**4.0**	**<0.001**	**0.23**
Error	0.67	110	0.006			
Stimulus	**23**	**1.0**	**23**	**8800**	**<0.001**	**0.99**
Stimulus*Age	**0.068**	**4.0**	**0.017**	**6.4**	**<0.001**	**0.32**
Error	0.15	55	0.003			
Test*Stimulus	0.017	2.0	0.009	2.6	0.078	0.045
Test*Stimulus*Age	**0.064**	**8.0**	**0.008**	**2.5**	**0.017**	**0.15**
Error	0.36	110	0.003			

Visual acuity with a surround box versus letters

Figure 3.16 shows visual acuities with HOTV letters surrounded by a box (top panel, HOTV Crowded arrangement) and flanked by letters (bottom panel, Cambridge Crowded arrangement). L acuities became adult-like later with flanking letters (7.4 ± 1.0 years) than with a surrounding box (6.2 ± 1.3 years) despite much steeper initial slopes with flanking letters (-1.7 ± 0.10 versus -0.82 ± 0.48) with L optotypes. LM acuities became adult-like at a similar age with a surrounding box (7.3 ± 1.2 years) and flanking letters (7.4 ± 1.1) despite much steeper initial slopes with flanking letters (-1.5 ± 0.3 versus -0.70 ± 0.26) with LM optotypes (see Table 3.14). With CM optotypes the slope was similar with a surrounding box (-0.57 ± 0.35) and with flanking letters (-0.40 ± 0.07). On average crowded CM acuity becomes adult-like at a later age than L or LM acuity, as it did for contour interaction.

Visual acuity measured with L and LM letters surrounded by a box or by letters is shown in Figure 3.17. Visual acuities were significantly higher (see Table 3.15) with flanking letters than with a surrounding box [F(1.0,50)=92, p<0.001] and this effect increased with younger children. Visual acuities were worse with LM than L optotypes [F(1.0,50)=19, p<0.001] and the difference between L and LM acuities increased with age [F(4.0,50)=19, p<0.001] from -0.012 ± 0.0131 logMAR difference with 3-4 year olds to 0.044 ± 0.011 and 0.052 ± 0.013 logMAR for 12-16 year olds and adults, respectively.

Figure 3.18 shows visual acuities are significantly worse (see Table 3.16) with CM than LM optotypes [F(1.0,50)=3100, p<0.001]. Especially for young children, the difference between LM and CM acuities when crowded (0.42 ± 0.04 logMAR, $2.6\times$) was smaller than when surrounded by a box (0.49 ± 0.03 logMAR, $3.1\times$). For CM optotypes (see Table 3.17), the effect of flanking letters or a surrounding box was not significantly different across age groups (p>0.05).

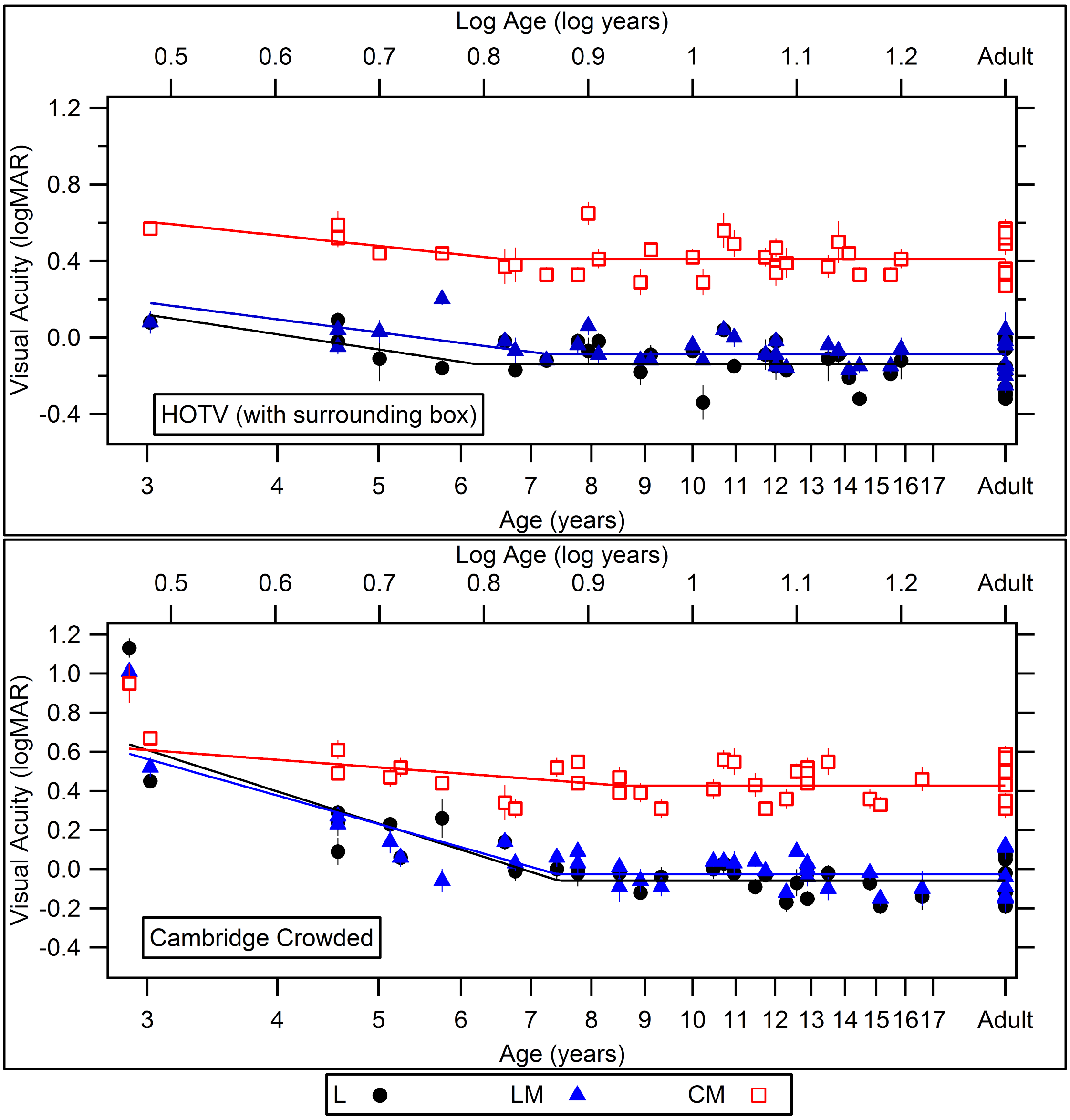


Figure 3.16: *Visual acuity estimates of children aged 3-16 years and adults measured using the staircase method with HOTV optotypes surrounded by a box or in the Cambridge Crowded configuration (flanking letters), both with a 1 stroke width target-flanker separation with a two-line fit to the data. Error bars indicate* ± 1 *SE.*

Table 3.14: *The initial line slope, intersection point and adult-like acuity for a 2-line-fit to L, LM and CM HOTV and Cambridge Crowded tests.*

Test		Initial slope	Adult VA (logMAR)	Critical age (log years)	Age (years)
HOTV	L	-0.82 ± 0.48	-0.14 ± 0.02	0.79 ± 0.10	6.2 ± 1.3
	LM	-0.70 ± 0.26	-0.09 ± 0.02	0.86 ± 0.07	7.3 ± 1.2
	CM	-0.57 ± 0.35	0.41 ± 0.02	0.82 ± 0.11	6.6 ± 1.3
Cambridge	L	-1.7 ± 0.1	-0.06 ± 0.01	0.87 ± 0.01	7.4 ± 1.0
Crowded	LM	-1.5 ± 0.3	-0.03 ± 0.02	0.87 ± 0.04	7.4 ± 1.1
	CM	-0.40 ± 0.07	0.43 ± 0.01	0.93 ± 0.04	8.6 ± 1.1

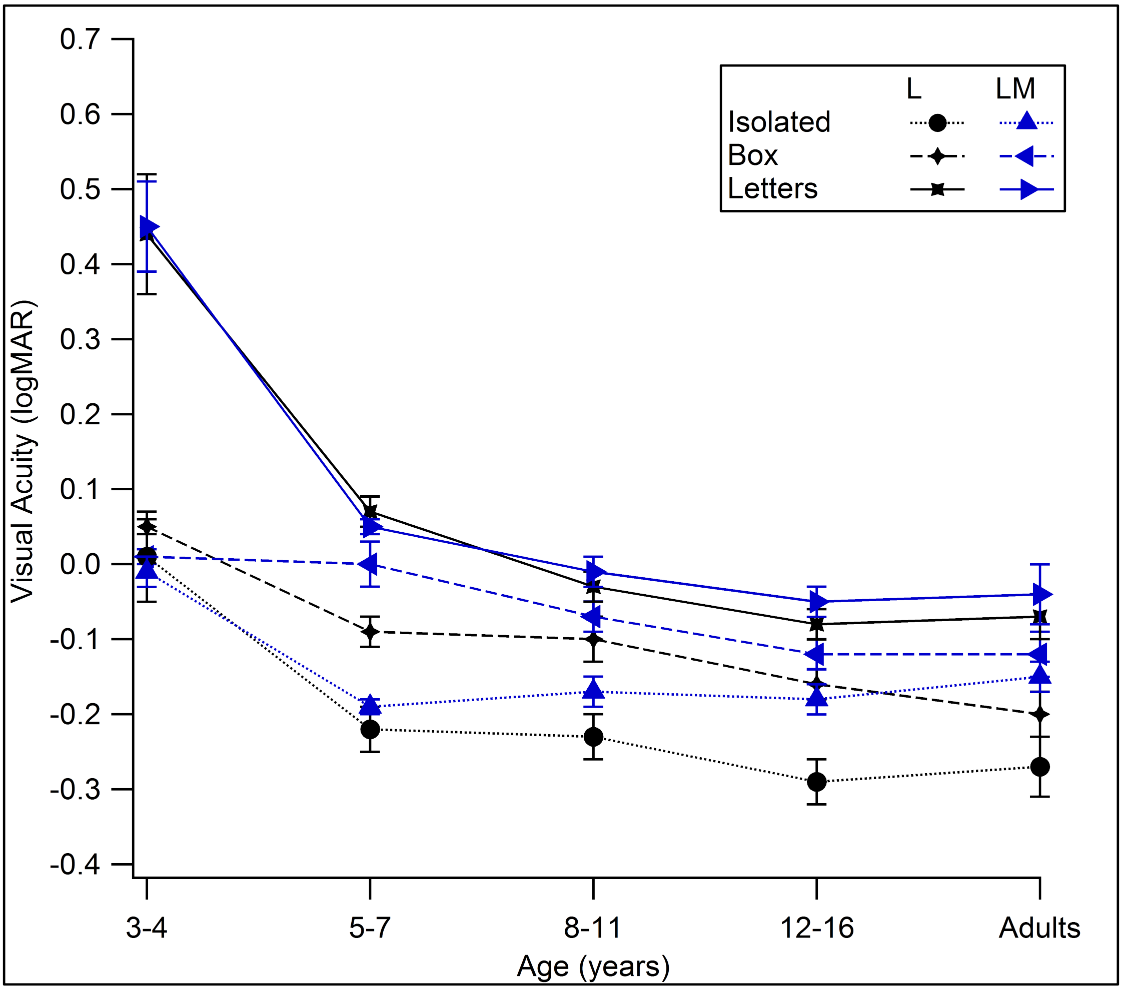


Figure 3.17: *Visual acuities measured with L and LM HOTV and Cambridge Crowded tests.*

Table 3.15: *A 2 (test) × 2 (stimulus) repeated measures ANOVA for L and LM HOTV and Cambridge Crowded tests with 1 between subject variable (age).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	**1.3**	**1.0**	**1.3**	**92**	**<0.001**	**0.65**
Test*Age	**0.97**	**4.0**	**0.24**	**17**	**<0.001**	**0.58**
Error	0.70	50	0.014			
Stimulus	**0.047**	**1.0**	**0.047**	**19**	**<0.001**	**0.28**
Stimulus*Age	**0.031**	**4.0**	**0.008**	**3.1**	**0.022**	**0.20**
Error	0.12	50	0.002			
Test*Stimulus	0.011	1.0	0.011	4.0	0.050	0.20
Test*Stimulus*Age	**0.044**	**4.0**	**0.011**	**4.2**	**0.005**	**0.25**
Error	0.13	50	0.003			

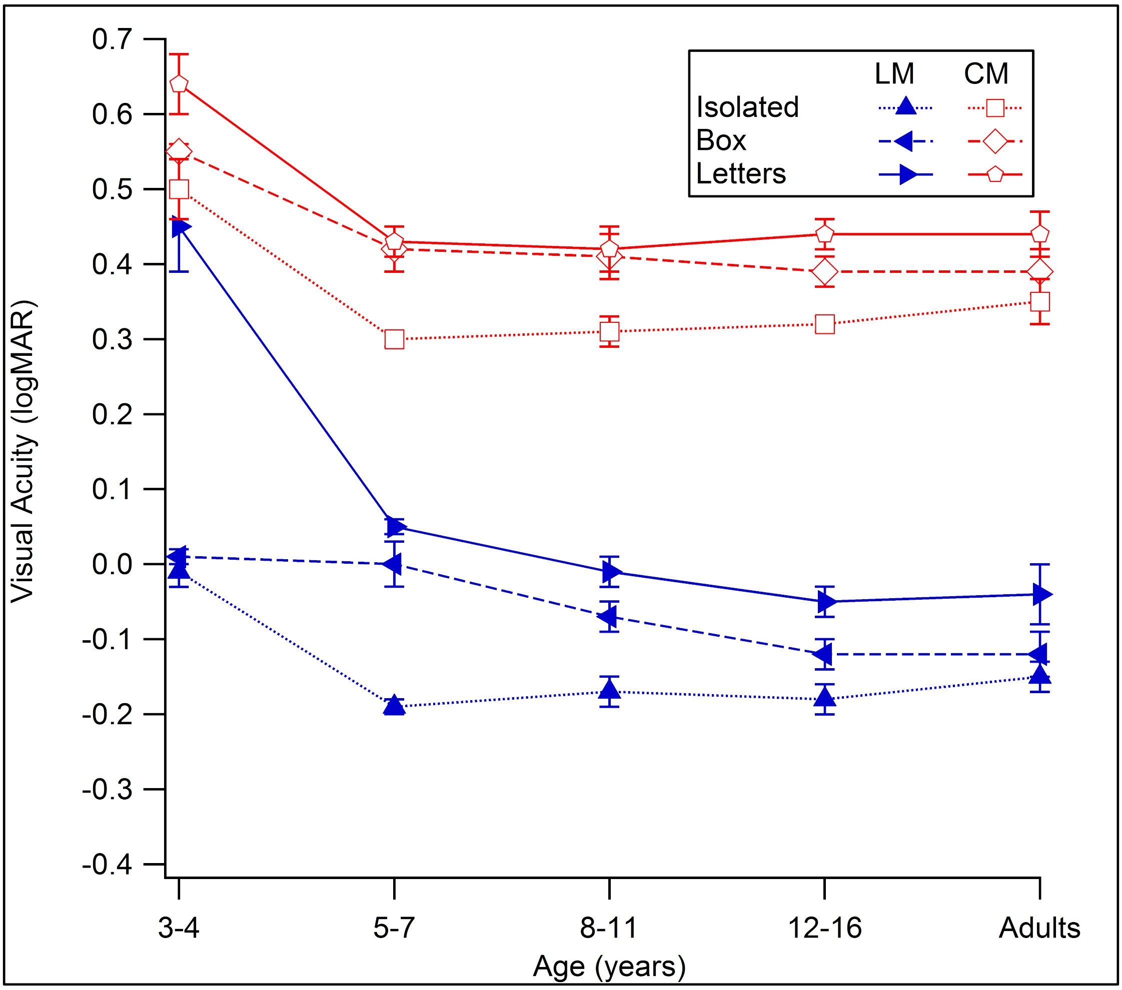


Figure 3.18: *Visual acuities measured with LM and CM HOTV and Cambridge Crowded tests.*

Table 3.16: *A 2 (test) × 2 (stimulus) repeated measures ANOVA for LM and CM HOTV and Cambridge Crowded tests with 1 between subject variable (age).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	0.45	1.0	0.45	58	<0.001	0.54
Test*Age	0.43	4.0	0.11	14	<0.001	0.53
Error	0.39	50	0.008			
Stimulus	11	1.0	11	3100	<0.001	0.98
Stimulus*Age	0.15	4.0	0.036	10	<0.001	0.46
Error	0.17	50	0.003			
Test*Stimulus	0.13	1.0	0.13	67	<0.001	0.57
Test*Stimulus*Age	0.23	4.0	0.057	29	<0.001	0.70
Error	0.099	50	0.002			

Table 3.17: *A 2 (test) repeated measures ANOVA for CM HOTV and Cambridge Crowded tests with 1 between subject variable (age).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Test	0.046	1.0	0.046	12	0.001	0.20
Test*Age	0.023	4.0	0.006	1.5	0.21	0.11
Error	0.19	50	0.004			

3.4.2 Development of contour interaction and crowding

Contour interaction

Contour interaction can be quantified by subtracting isolated visual acuity from flanked visual acuity in logMAR. The magnitude of contour interaction was not significantly different between L, LM and CM stimuli [$F(2.0,110)=1.0$, $p=0.37$] but there was a significant interaction with age [$F(8.0,110)=4.9$, $p<0.001$] although no significant consistent trend was noted (see Figure 3.19). This is more clearly shown by the averages in Figure 3.20.

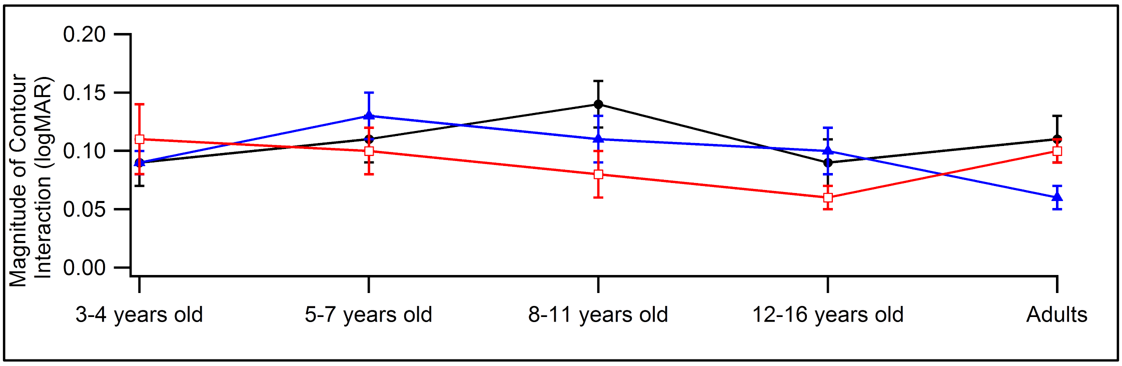


Figure 3.19: *The magnitude of contour interaction averaged across all participants in each age group (3-4, 5-7, 8-11, 12-16 year olds and adults) and across tests (Kay Pictures, Lea Symbols and HOTV) for L, LM and CM stimuli. Error bars indicate ±1SE.*

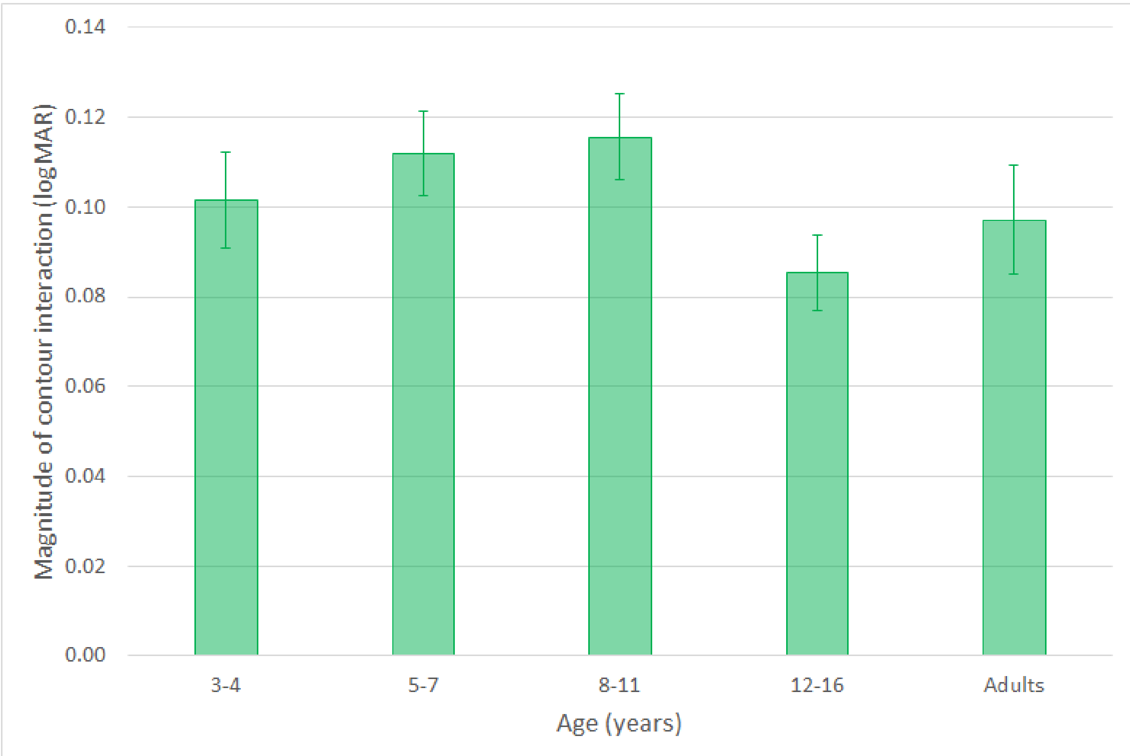


Figure 3.20: *The magnitude of contour interaction for 3-4, 5-7, 8-11 and 12-16 year olds and adults averaged across L, LM and CM Kay Pictures, Lea Symbols and HOTV tests.*

The average magnitude of contour interaction is significantly different between adults and 5-7 (p=0.019), 8-11 (p=0.023) and 12-16 (p=0.029) year olds but not with 3-4 year olds. Contour interaction was not significantly different between test (i.e. Kay Pictures, Lea Symbols and HOTV letters) [F(1.9,100)=0.79, p=0.45] (see Table 3.18). With 3-4 year olds, the variability in contour interaction was largest, being largest with HOTV

(0.072 ± 0.021 logMAR) and smallest with Lea Symbols (0.028 ± 0.028 logMAR).

Table 3.18: *A 3 (test) $\times$ 3 (stimulus) repeated measures ANOVA with 1 between subject variable (age) for the magnitude of contour interaction with L, LM and CM Kay Pictures, Lea Symbols and HOTV tests.*

	Sum of Squares	df	Mean Square	F	Sig.
Age	**0.097**	**4.0**	**0.024**	**5.3**	**0.001**
Error	0.25	54	0.005		
Test	0.009	1.9	0.005	0.79	0.45
Test*Age	**0.11**	**7.5**	**0.014**	**2.2**	**0.034**
Error	0.65	100	0.006		
Stimulus	0.008	2.0	0.004	1.0	0.37
Stimulus*Age	**0.16**	**8.0**	**0.020**	**4.9**	$<$**0.001**
Error	0.45	110	0.004		
Test*Stimulus	0.013	4.0	0.003	0.81	0.52
Test*Stimulus*Age	**0.21**	**16**	**0.013**	**3.2**	$<$**0.001**
Error	0.89	220	0.004		

Crowding

The magnitude of crowding with L, LM and CM stimuli is shown in Figure 3.21. Crowding was largest with 3 to 4 year olds with L (0.40 ± 0.05 logMAR) and LM (0.44 ± 0.04 logMAR) stimuli and reduced with age to 0.17 ± 0.03 logMAR and 0.18 ± 0.01 logMAR with 12 to 16 year olds and adults, respectively, with L stimuli and 0.11 ± 0.02 logMAR and 0.13 ± 0.01 logMAR with 12 to 16 year olds and adults, respectively, with LM stimuli. A repeated measures ANOVA showed an overall effect of age [F(4.0,45)=25, p<0.001]. There was a significant difference in the magnitude of crowding with L, LM and CM stimuli [F(2.0,90)=49, p<0.001] which was significantly different between ages [F(8.0,90)=6.7, p<0.001]. A one-way ANOVA to investigate the effects of crowding for each stimuli showed a significant difference in the magnitude of crowding between age groups with L [F(4,49)=11, p<0.001] and LM [F(4,49)=30, p<0.001] but not CM

[F(4,49)=1.9, p=0.13]. Tukey paired comparisons showed that the magnitude of crowding was significantly different from adults with 3 to 4 year olds (p<0.001) and 5 to 7 year olds (p=0.020 and p=0.009) with L and LM stimuli, respectively; with CM stimuli there were no significantly different pairs.

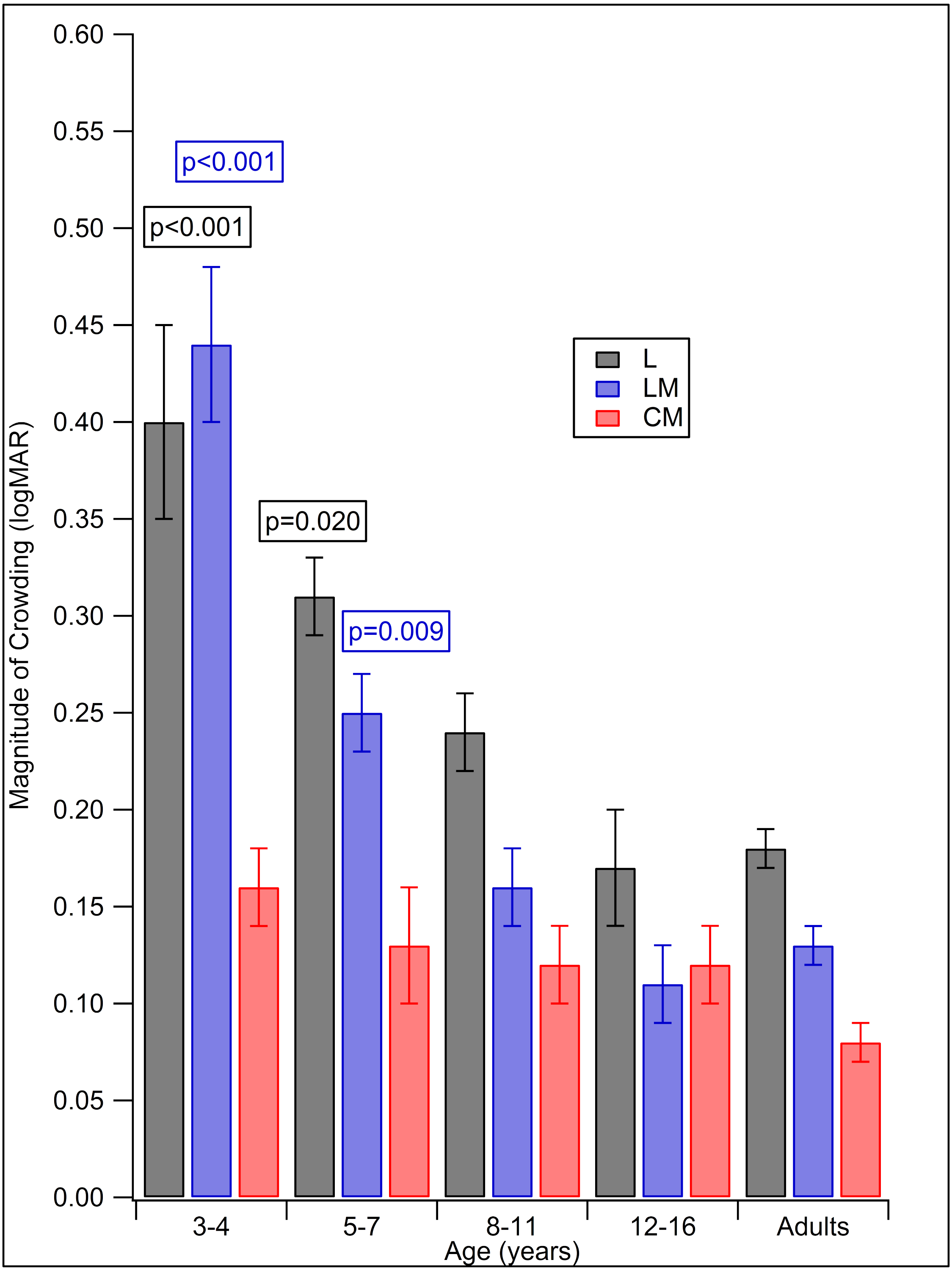


Figure 3.21: *The magnitude of crowding with L, LM and CM stimuli with points that are significantly different from adults marked.*

Crowding compared to contour interaction

The magnitude of crowding was much larger than the magnitude of contour interaction with L (0.16 ± 0.05 logMAR) and LM (0.13 ± 0.07 logMAR) but not CM (0.03 ± 0.02 logMAR) stimuli, as shown in Figure 3.22 where the difference between the two is plotted. The difference was largest with 3 to 4 year olds (0.33 ± 0.06, 0.37 ± 0.05 and 0.061 ± 0.030 logMAR for L, LM and CM stimuli, respectively) and reduced with age. The difference in adults was larger with L (0.090 ± 0.017 logMAR) and LM (0.068 ± 0.020 logMAR) stimuli than with CM stimuli (0.021 ± 0.013 logMAR). As shown in Figure 3.23, the overall pattern of both contour interaction and crowding are similar between L and LM stimuli, whereas with CM stimuli the magnitude of contour interaction, but not crowding, is similar to with L and LM stimuli.

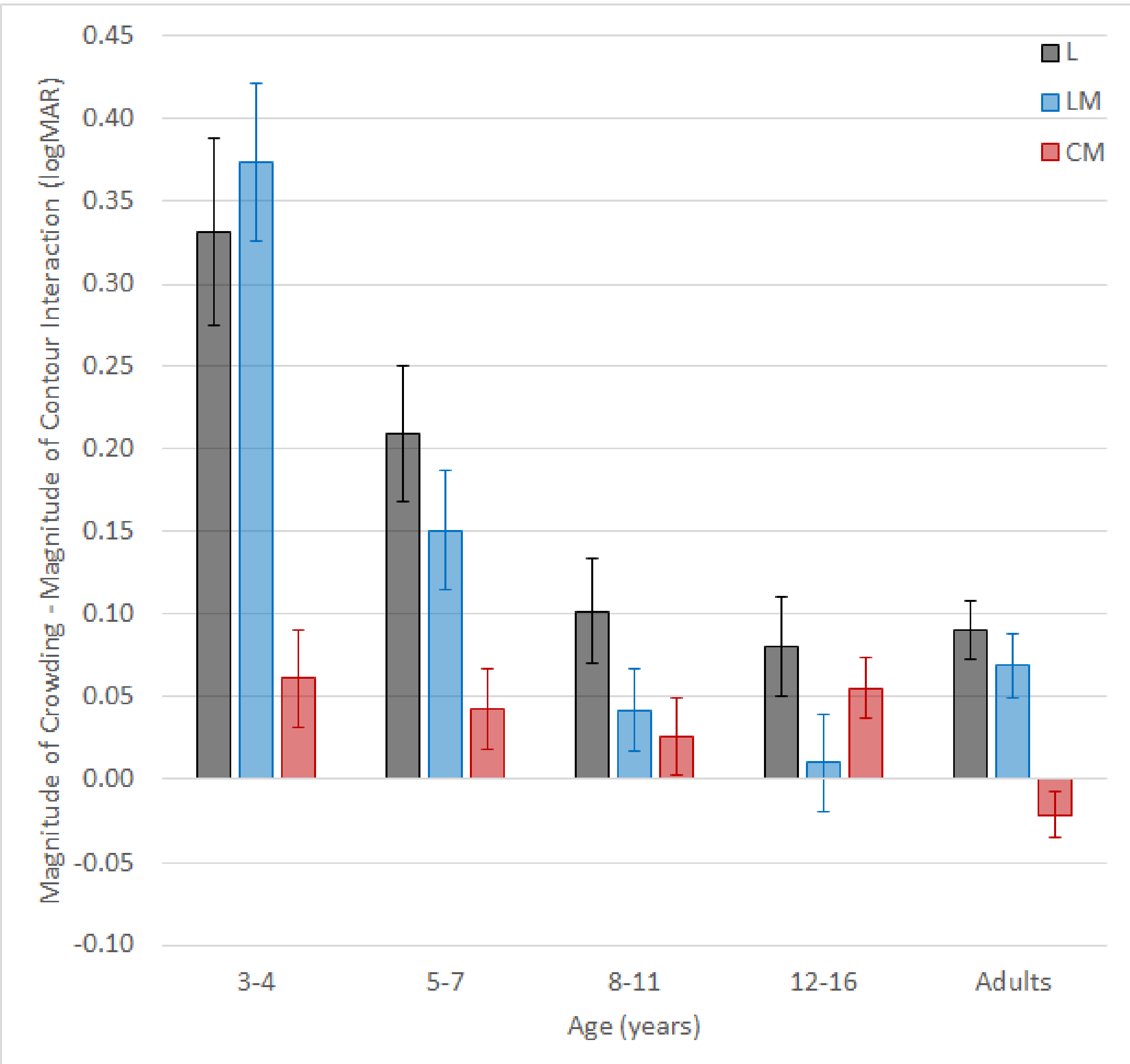


Figure 3.22: *The magnitude of contour interaction (with Kay Pictures, Lea Symbols and HOTV tests) subtracted from the magnitude of crowding (with the Cambridge Crowded test) for 3-4, 5-7, 8-11 and 12-16 year olds and adults with L, LM and CM optotypes.*

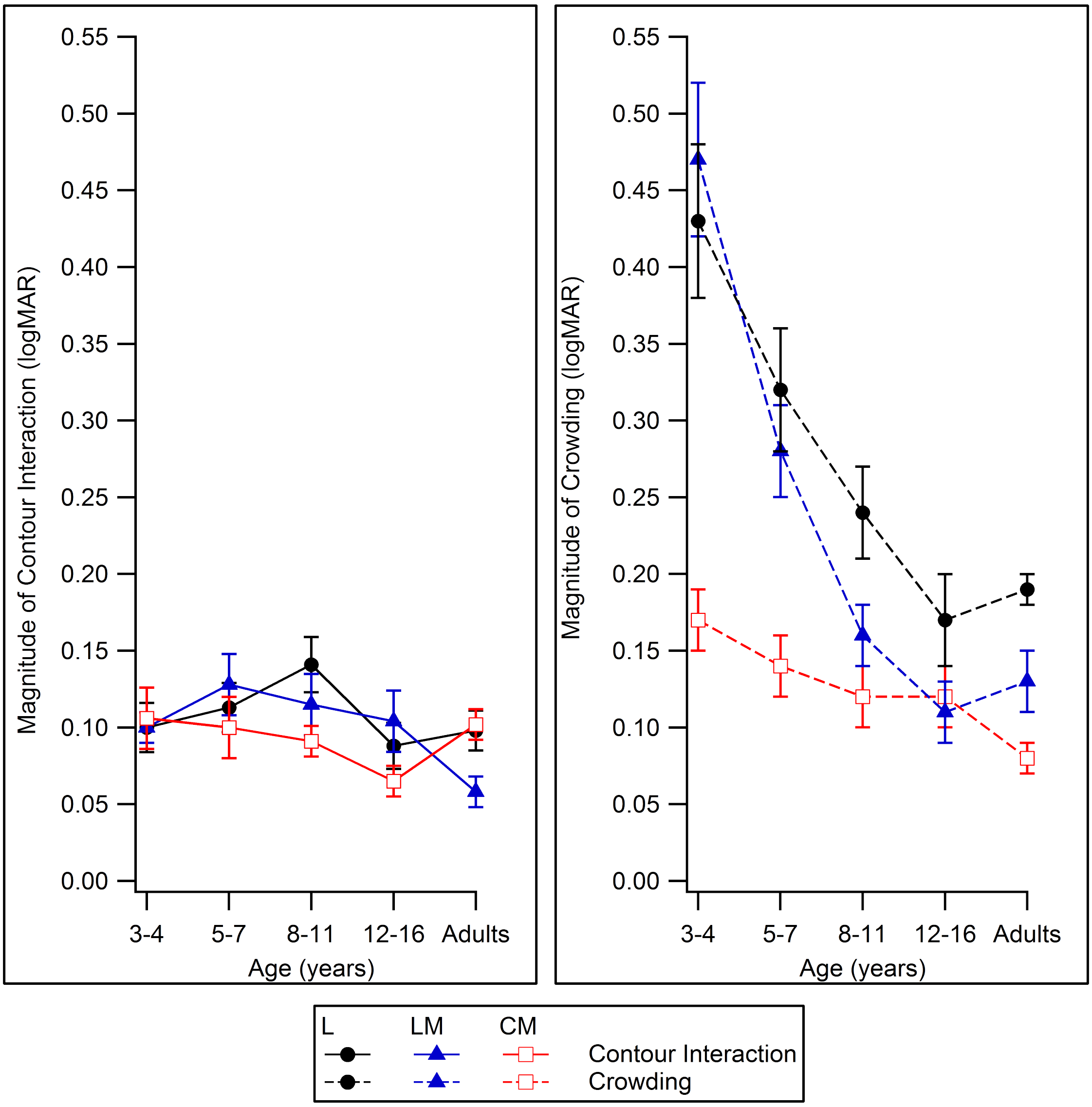


Figure 3.23: *The magnitude of contour interaction (left) and the magnitude of crowding (right) with L, LM and CM stimuli. Error bars indicate* $\pm 1SE$.

There was a significant reduction in both contour interaction and crowding with age with L and LM stimuli [F(4,50)=27, p<0.001] (see Table 3.19) and LM and CM stimuli [F(4.0,50)=36,p<0.001] (see Table 3.20). There was a significant interaction between test, stimulus and age [F(4.0,50)=29, p<0.001]. Contour interaction and crowding were similar in magnitude for CM stimuli, but crowding particularly for the younger children, was significantly larger than contour interaction; the effect became more similar as age increased.

Table 3.19: *A 2 (stimuli) × 2 (test) repeated measures ANOVA of the contour interaction and crowding for L and LM HOTV optotypes with 1 between subject variable (age).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Age	**0.84**	**4**	**0.21**	**27**	**<0.001**	**0.68**
Error	0.39	50	0.008			
Test	**1.1**	**1.0**	**1.1**	**120**	**<0.001**	**0.70**
Test*Age	**0.70**	**4.0**	**0.17**	**19**	**<0.001**	**0.60**
Error	0.47	50	0.009			
Stimuli	**0.042**	**1.0**	**0.042**	**13**	**0.001**	**0.20**
Stimuli*Age	**0.052**	**4.0**	**0.013**	**3.9**	**0.008**	**0.24**
Error	0.17	50	0.003			
Test*Stimuli	0.009	1.0	0.009	2.4	0.13	0.045
Test*Stimuli*Age	**0.051**	**4.0**	**0.013**	**3.5**	**0.014**	**0.22**
Error	0.18	50	0.004			

Table 3.20: *A 2 (stimuli) × 2 (test) repeated measures ANOVA of the contour interaction and crowding for LM and CM HOTV optotypes with 1 between subject variable (age).*

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Age	**0.64**	**4.0**	**0.16**	**36**	<**0.001**	**0.74**
Error	0.22	50	0.004			
Test	**0.30**	**1.0**	**0.30**	**110**	<**0.001**	**0.69**
Test*Age	**0.19**	**4.0**	**0.048**	**17**	<**0.001**	**0.58**
Error	0.14	50	0.003			
Stimuli	**0.14**	**1.0**	**0.14**	**41**	<**0.001**	**0.45**
Stimuli*Age	**0.12**	**4.0**	**0.030**	**8.7**	<**0.001**	**0.41**
Error	0.17	50	0.003			
Test*Stimuli	**0.16**	**1.0**	**0.16**	**42**	<**0.001**	**0.46**
Test*Stimuli*Age	**0.31**	**4.0**	**0.077**	**21**	<**0.001**	**0.63**
Error	0.18	50	0.004			

3.4.3 Visual acuity measurement differences between tests

Visual acuities for children grouped by age are shown for isolated optotypes in Figure 3.24 and for optotypes surrounded by a box in Figure 3.25. Visual acuity estimates with a surrounding box, as shown in Figure 3.25, are consistently highest (worst) with the Lea Symbols test. Repeated measures ANOVA (see Tables 3.9, 3.10, 3.12 and 3.13) revealed statistically significant differences between tests with L and LM isolated [F(2.0,110)=75, p<0.001] and surrounded [F(1.9,110)=78, p<0.001] optotypes. This was also the case when LM and CM isolated [F(2.0,110)=49, p<0.001] and surrounded [F(2.0,110)=69, p<0.001] optotypes were compared. The effect of test was significantly different across age group, for L and LM isolated [F(8.0,110)=3.9, p<0.001] and surrounded [F(7.7,110)=4.3, p<0.001]; and for LM and CM isolated [F(8.0,110)=5.1, p<0.001] and surrounded [F(8.0,110)=4.0, p<0.001] optotypes.

Differences in acuities between tests was not consistent across age group. The acuities measured with the Lea Symbols were consistently higher, but the Kay Pictures optotypes only gave better acuities with adults and older children.

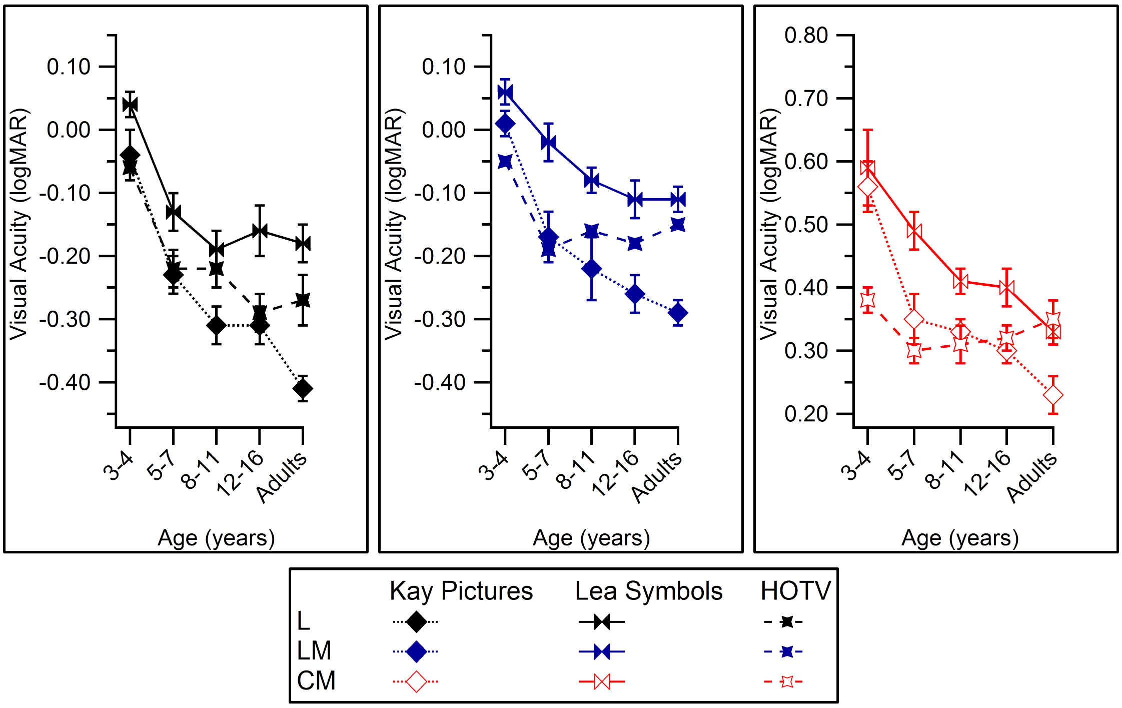


Figure 3.24: *Visual acuity averaged across age group for L, LM and CM isolated optotypes from the Kay Pictures, Lea Symbols and HOTV tests.*

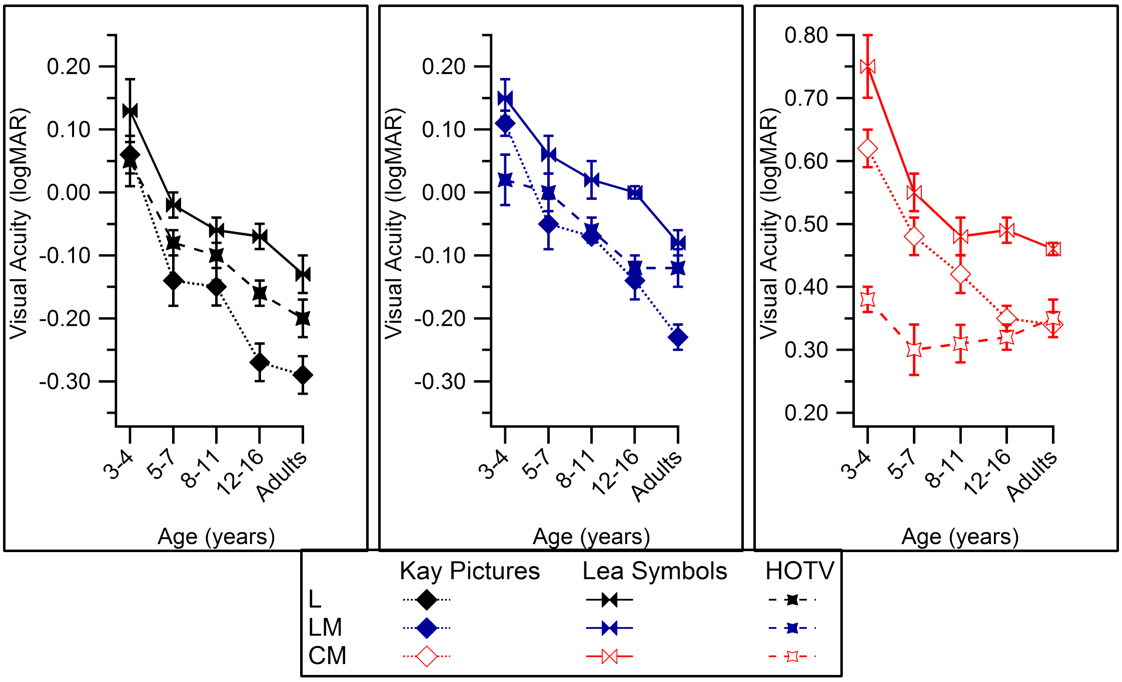


Figure 3.25: *Visual acuity averaged across age group for L, LM and CM optotypes from the Kay Pictures, Lea Symbols and HOTV tests with a surrounding box.*

3.4.4 Test re-test repeatability

Adults and, where possible, children did repeated measures of visual acuity using staircases. To assess the test-retest reliability, data for the two runs were plotted against each other. As has been done with previous similar research (Kay, 1983; Jones et al., 2003), a Pearson's correlation coefficient between Staircase 1 and Staircase 2 was calculated. Additionally, the standard deviation of the two acuity measurements was calculated. As demonstrated in 3.26a, the overall correlation coefficients for adults (n=10) were high: Kay Pictures (r=0.92), Lea Symbols (r=0.92) and HOTV letters (r=0.98). The average standard deviation was 0.14 ± 0.01 logMAR with Kay Pictures, lowest with Lea Symbols (0.10 ± 0.01 logMAR) and highest with HOTV letters (0.16 ± 0.01 logMAR). Children who did repeat staircases (n=19) were aged from 3 years 3 months to 16 years 6 months (mean 9.0 ± 4.1 years) and were spread across all age groups: 3-4 years old (n=4), 5-7 years old (n=3), 8-11 years old (n=4) and 12-16 years old (n=8). Correlation coefficients from children were also high (see Figure 3.26b): Kay Pictures (r=0.90), Lea Symbols (r=0.95) and HOTV letters (r=0.93) but the average standard deviation was smaller with children than for adults with Kay Pictures (0.08 ± 0.02 logMAR), Lea Symbols (0.05 ± 0.01 logMAR) and HOTV letters (0.06 ± 0.01 logMAR).

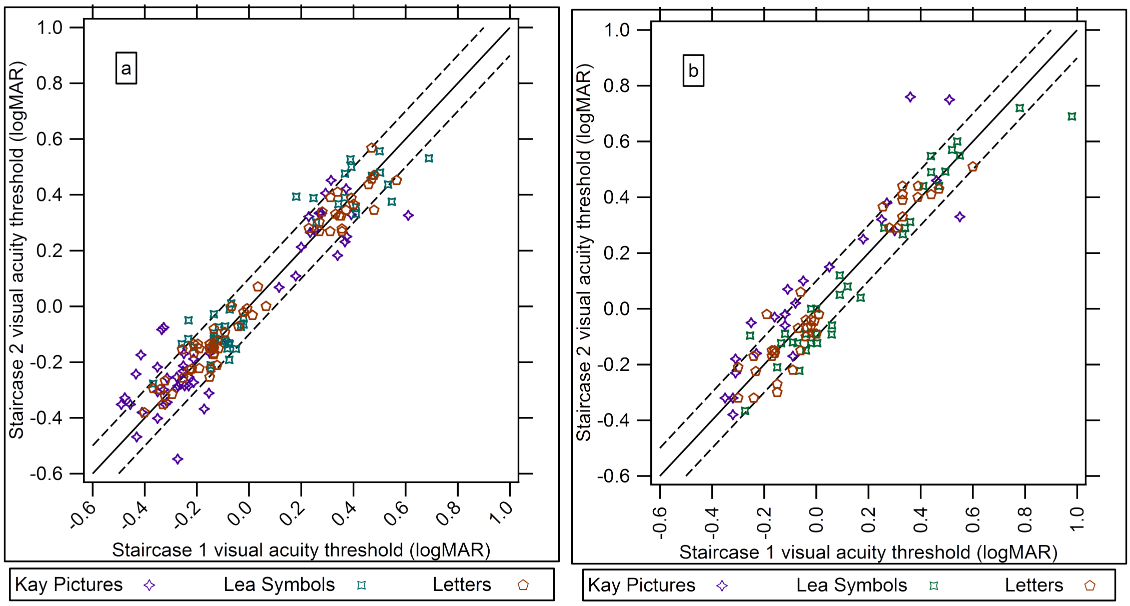


Figure 3.26: *(a) Adult (left) and (b) child (right) visual acuities measured with L, LM and CM Kay Pictures, Lea Symbols, HOTV and Cambridge Crowded tests, with and without "crowding" features, with the first measurement plotted against the second measurement for each test. Pearson correlation coefficients were calculated for Kay Pictures (r=0.92 and r=0.90), Lea Symbols (r=0.92 and r=0.95) and letters (r=0.98 and r=0.83) with adults and children, respectively. The solid line indicates a 1:1 fit and the dotted lines indicate 0.1 logMAR above and below the 1:1 fit line.*

The test-re-test visual acuity measurements for L, LM and CM stimuli were also separately plotted for adults (Figure 3.27) and children (Figure 3.28). Here, correlation coefficients (see Table 3.21) were higher with children than in adults for L (r=0.93 vs 0.73), LM (r=0.96 vs 0.76) and CM (r=0.96 vs 0.66) stimuli. The smaller correlation coefficients with children could be due to larger acuity ranges with children than adults for L (0.73 versus 0.55 logMAR), LM (0.64 versus 0.44 logMAR) and CM (0.79 versus 0.62 logMAR). Standard deviations were similar across stimulus types but were smaller for children than adults with L (0.11 ± 0.01 versus 0.05 ± 0.01 logMAR), LM (0.10 ± 0.01 versus 0.06 ± 0.01 logMAR) and CM (0.10 ± 0.01 versus 0.04 ± 0.02 logMAR). Across all tests and stimulus types, the Pearson correlation coefficients were similar for children (r=0.85 ± 0.12) and adults (r=0.83 ± 0.13) but the standard deviations were smaller for children (0.05 ± 0.01 logMAR) than adults (0.11 ± 0.01 logMAR).

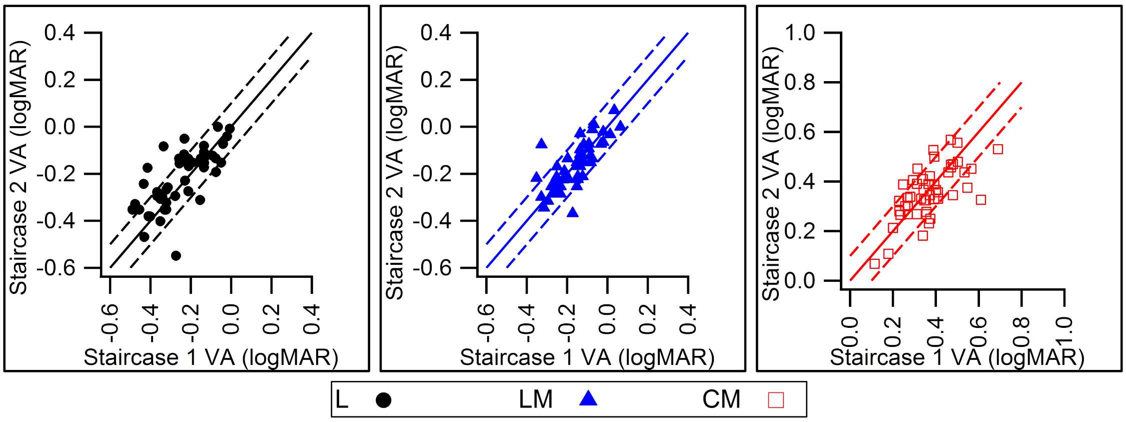


Figure 3.27: *Adult visual acuities measured with L, LM and CM Kay Pictures, Lea Symbols, HOTV and Cambridge Crowded tests, with and without "crowding" features, with the first measurement plotted against the second measurement for each stimulus type. Pearson correlation coefficients were calculated for L (r=0.73), LM (r=0.76) and CM (r=0.66). The solid line indicates a 1:1 fit and the dotted lines indicate 0.1 logMAR above and below the 1:1 fit line.*

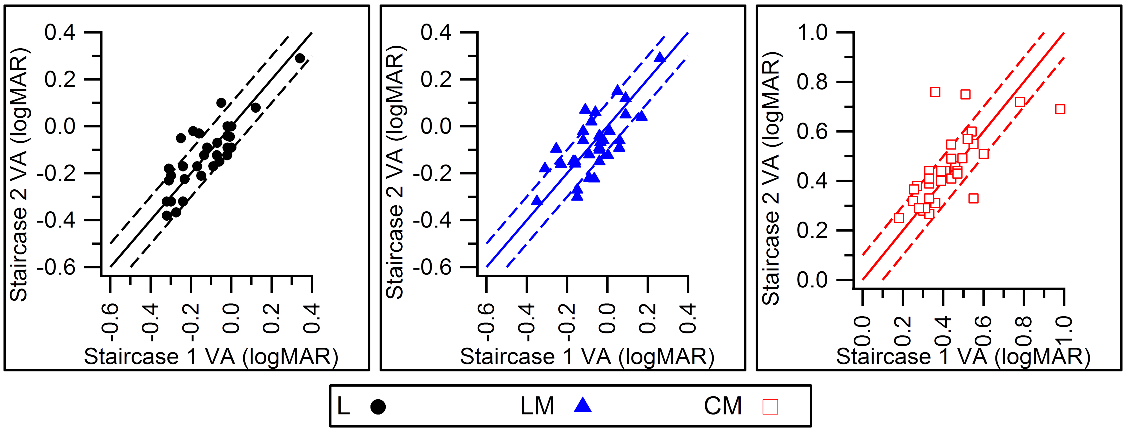


Figure 3.28: *Child visual acuities measured with L, LM and CM Kay Pictures, Lea Symbols, HOTV and Cambridge Crowded tests, with and without "crowding" features, with the first measurement plotted against the second measurement for each stimulus type. Pearson correlation coefficients were calculated for L (r=0.93), LM (r=0.96) and CM (r=0.96). The solid line indicates a 1:1 fit and the dotted lines indicate 0.1 logMAR above and below the 1:1 fit line.*

Table 3.21: *Pearson correlation coefficients and range of acuities for Kay Pictures, Lea Symbols and HOTV letters, and L, LM and CM stimuli.*

	Children		Adults	
	Correlation	Acuity range	Correlation	Acuity range
L	r=0.93	0.73 logMAR	r=0.73	0.55 logMAR
LM	r=0.96	0.64 logMAR	r=0.76	0.44 logMAR
CM	r=0.96	0.79 logMAR	r=0.66	0.62 logMAR
Kay Pictures	r=0.90	1.15 logMAR	r=0.92	1.16 logMAR
Lea Symbols	r=0.95	1.34 logMAR	r=0.92	1.06 logMAR
HOTV letters	r=0.93	0.92 logMAR	r=0.98	0.97 logMAR
Average	r=0.83		r=0.85	

3.5 Discussion

3.5.1 Development of visual acuity

Adult-like acuities

Visual acuity is poor in infants and improves with age until it reaches adult-like levels. There is very little consensus about the age at which visual acuity reaches adult-like levels; some studies using gratings indicate that acuity is adult-like by 3-6 years of age (Catford and Oliver, 1973; Mayer et al., 1982; Birch and Hale, 1988; Mayer et al., 1995; Ellemberg et al., 1999; Stiers et al., 2003; Lewis and Maurer, 2005), whereas other studies using optotype recognition indicate that visual acuity becomes adult-like somewhere between 5 and 10 years of age (Atkinson and Braddick, 1982; Simons, 1983; Stiers et al., 2003; Lai et al., 2007; Drover et al., 2008; Pan, Tarczy-Hornoch, Cotter Susan, Wen, Borchert, Azen and Varma, 2009). The results of the current study, using a 2-line-fit to the data, indicate that visual acuity with standard luminance optotypes becomes adult like at 8.0 ± 1.1 years of age with individual isolated optotypes and at 8.1 ± 1.2 years of age with contour interaction. When measured with standard luminance letters flanked by letters visual acuity became adult-like earlier (7.4 ± 1.0 years of age) than when isolated, or with a surrounding box. The steeper slope with flanking letters (-1.7 ± 0.1) than with a box (-0.76 ± 0.14) or isolated optotypes (-0.82 ± 0.10) is driven by the much higher acuities of the youngest children (3 years old) who were tested with letters flanked by letters.

These crowded acuities may be high due to the cognitive complexity of the task (possibly contributing to the crowding mechanism) and this could steepen the slope, resulting in the estimate of the age at which visual acuities become adult-like earlier. Artificially holding the slope at the average of the initial slopes for L stimuli with a surrounding box (-0.76) increases the estimate of the point at which acuities become adult-like to 12.4 ± 1.2 years old.

Noise

Visual acuity measured with LM stimuli was significantly higher ($p<0.001$) than when measured with L stimuli, although the effect was dependent on age ($p \leq 0.001$) and was least (0.017 ± 0.009 logMAR) for 3 to 4 year olds, increasing with age to 0.088 ± 0.024 logMAR with adults. The LM stimuli, unlike the L stimuli, have incorporated noise, which when above the estimated internal noise level of the participant (equivalent noise) raises the detection threshold (Pelli and Farell, 1999). This effect could explain the higher (worse) acuity thresholds for the noisy LM stimuli (than for the noiseless L stimuli) in older children and adults. Similar acuities for L and LM stimuli could indicate higher internal noise in the youngest children (3 to 4 year olds).

Contrast and luminance modulated optotypes

Visual acuity measured with CM stimuli was significantly worse (mean 0.51 ± 0.01 logMAR) than when measured with LM stimuli. This is in line with the expected 0.3 to 0.5 logMAR higher (2 to 3 times worse) acuities expected with CM compared to LM stimuli in normal adults if CM stimuli are processed in V2 or above (see Section 2.5.1 for further discussion). This is in line with the 0.51 ± 0.01 logMAR higher ($3.2\times$ worse) acuities found in this experiment with CM than LM stimuli which was not significantly different between age groups ($p>0.05$). The difference between acuities obtained with LM and CM stimuli is likely to have been smaller if equally visible stimuli had been used (Hairol et al., 2013) but this would be too time consuming to do with children or for use clinically. In adults, contour interaction effects were consistently stronger for CM optotypes, however for children the results were more variable.

3.5.2 Development of contour interaction and crowding

Contour interaction is the phenomenon where resolution acuity is degraded by the spatial arrangement of contours in the visual field (Flom, Weymouth and Kahneman, 1963), such as a surrounding box or flanking bars. Crowding is similar to, and inclusive of, contour interaction but includes the effect of surrounding objects, such as flanking optotypes, in addition to nearby contours (for reviews, see Levi, 2008; Whitney and Levi, 2011). Some pre-literate visual acuity tests have a mixture of contour interaction and crowding, for example a line of optotypes with a surrounding box. For both adults and children, visual acuity improves systematically as the flankers move away from the target (Bondarko and Semenov, 2005; Norgett and Siderov, 2014) but it has also been reported that contour interaction/crowding is more extensive and of greater magnitude for children than for adults (Atkinson et al., 1986, 1988; Jeon et al., 2010; Masgoret et al., 2011; Norgett and Siderov, 2014). The results of the current study on the magnitude of contour interaction and crowding will now be discussed.

When is contour interaction adult-like?

The results of the current study show that there was no significant effect of test or stimulus on the magnitude of contour interaction. Collapsed across test and stimulus, the magnitude of contour interaction (0.010 ± 0.003 logMAR) was not significantly different between 3 to 4 year olds (0.10 ± 0.01 logMAR) and adults (0.10 ± 0.01 logMAR). Fern and Manny (1986) obtained a similar magnitude of contour interaction with their youngest (2 years old, 0.09 ± 0.01 logMAR) and oldest (7 years old, 0.08 ± 0.03 logMAR). The slightly smaller magnitude of contour interaction found by Fern and Manny (1986) with bars flanking a Landolt C is expected due to the larger target-flanker separation distance (2.5 stroke widths) that they used compared to the current study (1.0 stroke width) and is similar to the magnitude of contour interaction found in Experiment 1 with normal adults with 2 to 3 stroke widths target-flanker separation (0.08 ± 0.01 logMAR).

When is crowding adult-like?

The magnitude of crowding reduces with age. The magnitude of crowding was much larger than the magnitude of contour interaction with L and LM stimuli (0.32 ± 0.13 and 0.40 ± 0.11 logMAR larger, respectively) but with CM stimuli the magnitude of contour interaction and crowding were not different across age (difference of -0.02 ± 0.04 logMAR). The magnitude of crowding was largest with 3 to 4 year olds but the difference between 3 to 4 year olds and adults was largest with L (0.24 ± 0.03 logMAR, $p<0.001$) and LM (0.35 ± 0.04 logMAR, $p<0.001$), and smallest with CM (0.09 ± 0.02 logMAR, $p>0.05$). The magnitude of crowding was significantly larger with 5 to 7 year olds than adults with L (0.13 ± 0.04, $p=0.020$) and LM (0.15 ± 0.03 logMAR, $p=0.009$) stimuli. With L, LM and CM stimuli the magnitude of crowding is not significantly different from adults with 8 to 11 or 12 to 16 year olds ($p>0.05$).

3.5.3 Comparison with previous studies: Acuities with standard luminance (L) Kay Pictures, Lea Symbols and HOTV tests

Results of previous studies have suggested that a 1 to 2 line over-estimation of visual acuity is expected when testing using the Kay Pictures test on children (Norgett and Siderov, 2011; Shah et al., 2012), with ages 4.8 to 9.8 years and 4 to 15 years (mean age 8 years) respectively. Figure 3.24 indicates that this may not be the same with 3 to 4 year olds as it is for 5 to 7 year olds. These results therefore indicate that the inter-test acuity differences may not be consistent across age. The lower acuities obtained by Shah et al. (2012) and Norgett and Siderov (2011) with Kay Pictures may have been influenced by comparing only with letters. Lower testability with letters compared to Kay Pictures (Kay, 1983; Hered et al., 1997; Vision in Preschoolers (VIP) Study Group, 2004; Kvarnström and Jakobsson, 2005) may have produced worse acuities with letters due to difficulty with the task rather than optotype differences. Lea Symbols and Kay Pictures were both designed to improve testability with 3 to 4 year olds (Hyvärinen et al., 1980; Kay, 1983) and therefore testability with this age group should be similar and the results in this chapter indicate that the inter-test acuity difference between Kay Pictures and Lea Symbols is smallest with 3 to 4 year olds and increases with age. Therefore, results of studies that have used adults to estimate acuity differences between tests may not apply to expected results in young children. This is important because these charts are primarily used with young children.

Anstice et al. (2017*b*) measured the visual acuities of 4 to 9 year olds (mean 6.6 years old) with commercially available versions of the Kay Pictures, Lea Symbols and the HOTV test and found the highest (worst) acuities with Lea Symbols (-0.03 ± 0.02 logMAR), acuities of -0.07 ± 0.03 logMAR with the HOTV test and the lowest (best) acuities with Kay Pictures (-0.19 ± 0.03) (Anstice et al., 2017*a*). The acuities obtained by Anstice et al. (2017*a*) are similar to the average acuity of 4 to 9 year olds in Experiment 2 for isolated and flanked acuities with the Lea Symbols (-0.06 ± 0.02 logMAR, mean age 6.5 years), the HOTV test (-0.14 ± 0.02 logMAR, mean age 7.2 years) and Kay Pictures (-0.16 ± 0.02 logMAR, mean age 6.7 years).

Additional considerations for luminance modulated (LM) and contrast modulated (CM) optotypes

Visual acuities have not previously been measured in children with L, LM and CM optotypes. The results in the present study indicate that visual acuities are significantly worse with LM than L stimuli with children (p<0.001) like was found with adults in Experiment 1 (p=0.028). The difference between acuities with L and LM stimuli increased significantly with age (p=0.001). This finding may indicate that the level of internal noise is higher in children, thereby reducing the effect of noise within the stimuli.

The development of visual acuity with CM stimuli is largely unknown. Evidence exists of more immature acuities with CM than LM gratings (Lewis et al., 2007) and contrast thresholds becoming adult-like later with a CM large rotated C (after 12 years of age) than with an LM large rotated C (adult-like by 12 years of age). The present study found later adult-like acuities with CM (9.2 ± 0.4 years of age) than LM (8.0 ± 0.4 years of age) stimuli. A 2-line fit to the data also indicated a slower development of acuities with CM than LM stimuli. This is supported by the findings of Tang and Zhou (2009) who found an earlier but slower decline of contrast sensitivity to CM than LM stimuli and Faubert (2002) found a greater deficit in older adults (aged 64 to 79 years) with CM than LM stimuli. The findings and this study and those of Faubert (2002) and Tang and Zhou (2009) indicate that CM stimuli require higher-level or more stages of processing than LM stimuli.

3.6 Conclusion

Visual acuities develop more slowly and become adult-like later with CM compared to L and LM stimuli, which develop at a similar rate to one another and become adult-like at a similar age. The magnitude of contour interaction was similar across tests and between L (0.11 ± 0.01 logMAR), LM (0.10 ± 0.01 logMAR) and CM (0.09 ± 0.01 logMAR) stimuli. The rate at which acuities became adult-like was slower with CM crowded optotypes but faster with crowded L and LM optotypes. The magnitude of crowding is larger than the magnitude of contour interaction, but this difference is smaller with CM optotypes (0.03 ± 0.01 logMAR difference) than L and LM optotypes (0.13 ± 0.03 and 0.09 ± 0.03 logMAR difference, respectively). With CM optotypes, the difference between the magnitude of contour interaction and crowding was similar across all age groups (0.01 ± 0.04 logMAR with the youngest children and 0.02 ± 0.01 logMAR with adults), whereas with L and LM stimuli the magnitude of crowding was largest compared to the magnitude of contour interaction with the youngest age group (0.24 ± 0.06 and 0.18 ± 0.07 logMAR, respectively) and the difference decreased with age (0.09 ± 0.02 and 0.05 ± 0.02 logMAR with adults).

Chapter 4

Summary of results and conclusions

The potential usefulness of a crowded contrast-modulated visual acuity test designed for testing children for earlier detection of amblyopia, was investigated. Visual acuity was measured with standard luminance (L), luminance modulated (LM) and contrast modulated (CM) optotypes surrounded by contour interaction and crowding features. Measures were made in normal healthy adults and children aged 3 to 16 years old.

4.1 General discussion

4.1.1 Crowding and contour interaction

The placement of surrounding features revealed that more consistent contour interaction and crowding effects are found if units of stroke width are used to specify target-flanker separation. Placing spatial features one stroke-width from the target maximises the effects of contour interaction and crowding on visual acuity. It also results in steeper underlying psychometric function slopes, increasing sensitivity of the visual acuity measure to change, e.g., with normal development, amblyopia or treatment.

Contour interaction and crowding in normal adults were investigated for different child-friendly acuity optotypes in Experiment 1. For adults, contour interaction effects were stronger for CM than LM optotypes, although crowding for CM stimuli were similar to contour interaction effects; whereas for L and LM optotypes, crowding was significantly stronger. In Experiment 2, contour interaction and crowding were measured in normal children. No significant effect of test optotype (Kay Pictures, Lea Symbols, HOTV) or stimulus type (L, LM, CM) on the magnitude of contour interaction was found for children aged 3 to 16 years. In Figures 4.1a and 4.1b, visual acuities for isolated optotypes versus visual acuities for optotypes within a box, were collapsed across test for different ages, including adults. The magnitude of contour interaction was not significantly different between 3-4 year olds (0.10 ± 0.01 logMAR) and adults (0.10 ± 0.01 logMAR), nor for CM (Figure 4.1b), versus LM or L stimuli (Figure 4.1a). This finding is demonstrated by noting the position of the data points in relation to finely dotted lines set 0.1 logMAR above each isolated acuity. If the data points coincided with the black line, this would have indicated no contour interaction, because the isolated and surrounded visual acuity would then be the same.

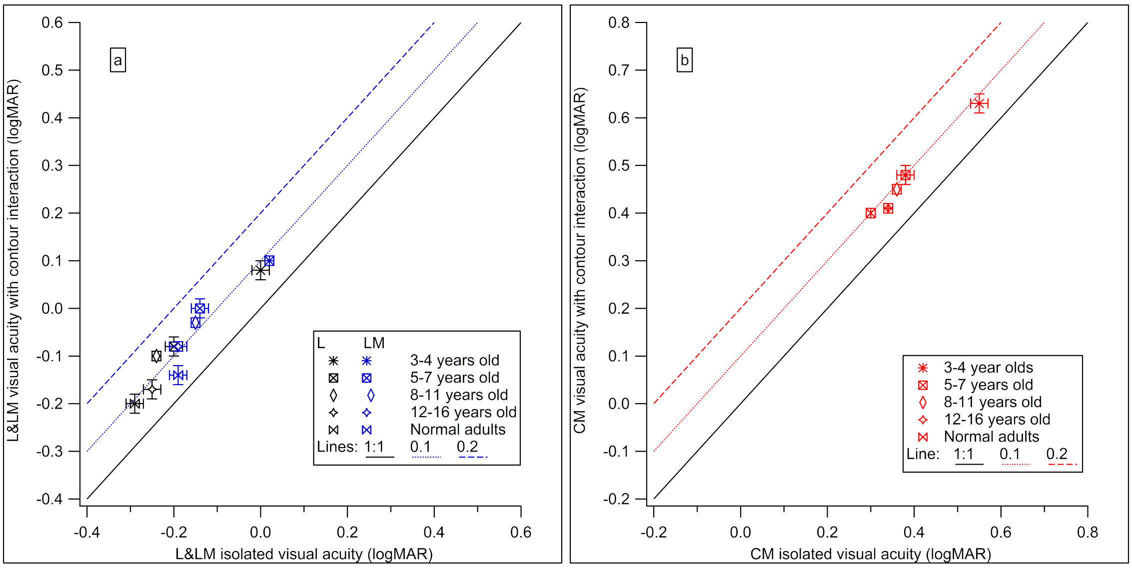


Figure 4.1: *Isolated visual acuities plotted against visual acuities measured with contour interaction features for 3-4, 5-7, 8-11, 12-16 year olds and adults with (a) L and LM stimuli (left) and (b) CM stimuli (right).*

Flankers that are similar to the target optotype surrounding it, (i.e., crowding), produce greater spatial interaction effects than a box (contour interaction) with L and LM stimuli in adults (0.16 ± 0.01 versus 0.08 ± 0.01 logMAR), aand also increase the sensitivity of the test to change, as indicated by a steeper psychometric function slope. However for CM stimuli, the magnitude of contour interaction and crowding were similar to each other. Data for children and adults are combined and shown in Figures 4.2a and 4.2b.

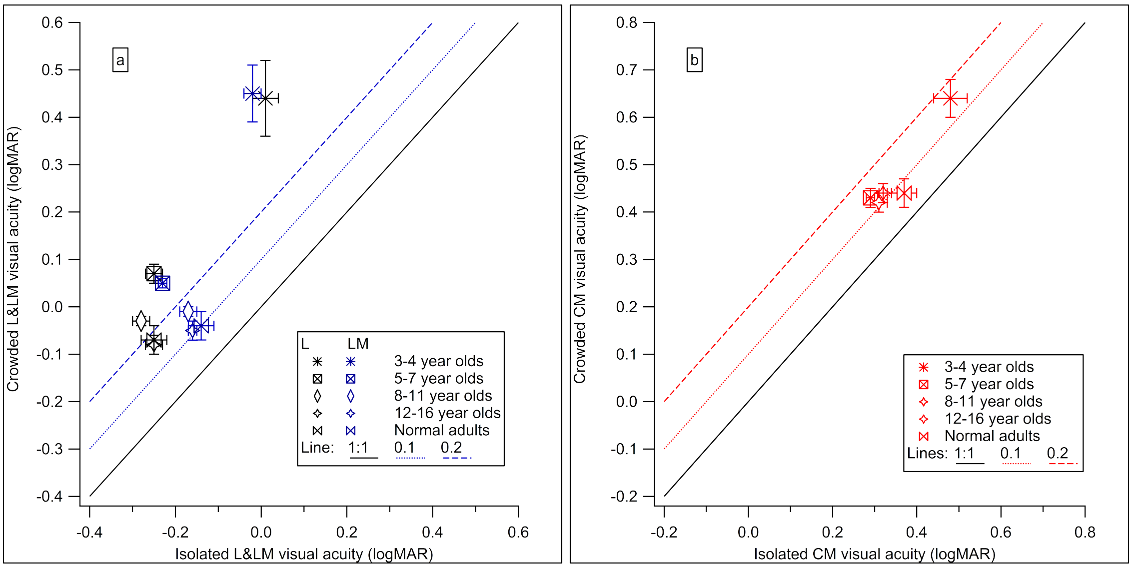


Figure 4.2: *Isolated visual acuities plotted against crowded visual acuities for 3-4, 5-7, 8-11, 12-16 year olds and adults with (a) L and LM stimuli (left) and (b) CM stimuli (right).*

Figure 4.2a shows that the magnitude of crowding for L and LM stimuli reduces significantly with increasing age (from 0.45 ± 0.07 to 0.16 ± 0.02 logMAR from 3-4 year olds to adults). Differences found between contour-interaction and crowding for L and LM stimuli particularly for young children (compare Figures 4.1a and 4.2a), reveal that other factors besides contour interaction, such as eye movements and attention, which change with development, contribute to crowding. With CM stimuli (Figure 4.2b) the magnitude of crowding reduces much less from 0.17 ± 0.02 logMAR with 3-4 year olds to 0.09 ± 0.01 logMAR with 12-16 year olds and adults.

It has been suggested (for example by: Flom, Heath and Takahashi, 1963; Flom, Weymouth and Kahneman, 1963; Toet and Levi, 1992; Levi, 2008; Siderov et al., 2012) that foveal crowding only occurs over small distances (up to 4-6 arcmin), being far more extensive in the normal periphery. In normal adults and children, given the acuities that were measured, the target and flankers are within this 6 arcmin zone. However with the CM crowded test, only part of the flanking letters would fit into this zone assuming a 1 stroke width target-flanker separation. This might explain why there is a much smaller difference between contour interaction and crowding with CM stimuli, except that Hairol et al. (2013) revealed zones for CM stimuli that also scaled with CM acuity in which case, this explanation is unlikely. An alternative explanation for increased crowding with L/LM stimuli versus CM stimuli might be that L/LM stimuli are more familiar to participants, so that similarity and grouping (Gestalt Principles) behave differently for L/LM versus CM stimuli. A similar but weaker trend of slightly stronger crowding than contour interaction occurs across age for CM stimuli. This suggests that grouping of the target and the flankers by familiarity is greater in children for L/LM optotypes, than for CM optotypes, leading to enhanced L/LM crowding.

4.1.2 Visual acuities

Contrast modulated compared to luminance modulated tests

There is evidence that CM stimuli are processed in a more binocular neural region (Hairol and Waugh, 2010; Wong et al., 2001, 2005), possibly V2 (Sheth et al., 1996; Wong et al., 2001) or higher (Calvert et al., 2005; Larsson et al., 2006; Chung et al., 2007, 2008*a*). The receptive field sizes in V2 and higher cortical areas are larger than the receptive field sizes in V1, being 2 to 3 times larger in V2 than V1 (Smith et al., 2001). Spatial summation areas estimated psychophysically for CM Gaussian blob stimuli are also 2 to 3 times larger than for LM Gaussian blob stimuli (Sukumar and Waugh, 2007). Visual acuity differences between LM and CM optotypes found in Experiment 1 with normal adults amount to 0.55 ± 0.05 logMAR ($3.5\times$) worse acuity for CM optotypes, and in Experiment 2 with normal children, visual acuities are on average 0.51 ± 0.01 logMAR, ($3.2\times$) worse for CM optotypes. The slightly higher differences found in Experiments 1 and 2 compared with Hairol et al.'s results in which they found that CM acuities for C stimuli were about 0.3 logMAR worse, could be due to the LM and CM stimuli not being equally visible in the current study. Creating equally visible stimuli is not feasible in a clinical environment. Hairol et al. (2013) also did a control study with high contrast LM and CM stimuli that were not equally visible, which like in the current study, also resulted in higher differences between LM and CM acuities.

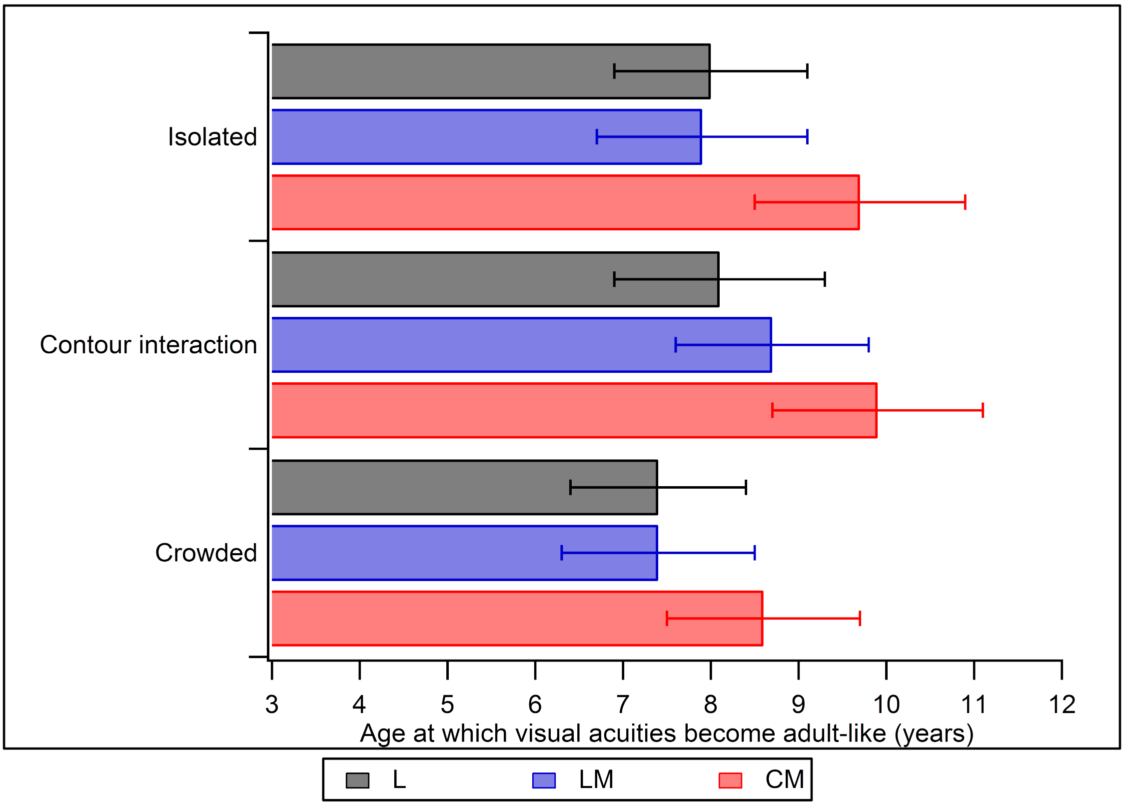


Figure 4.3: *The average age at which visual acuities become adult-like for L, LM and CM optotypes, isolated, with contour interaction features and with crowding features.*

In the current study, visual acuities (with and without crowding/contour interaction features) become adult-like later (see Figure 4.3 and Table 4.1) with CM (10.1 ± 3.5 years old), than with LM (8.3 ± 1.5 years old) optotypes, with a slower rate of development with CM, than L/LM stimuli. This is similar to results of previous studies investigating the nature of neural decline in normal ageing (Habak and Faubert, 2000; Faubert, 2002) who found that visual acuity deteriorated earlier and at a slower rate for CM, than L/LM stimuli.

Table 4.1: *Adult-like visual acuities calculated using a two-line-fit from Experiment 2.*

Test	Format	L	LM	CM	Average
Kay	Isolated	9.2 ± 1.1	9.0 ± 1.1	9.8 ± 1.2	9.3 ± 0.4
Pictures	With CI	10.5 ± 1.2	8.7 ± 1.0	15.3 ± 1.2	11.5 ± 3.4
Lea	Isolated	7.6 ± 1.1	9.4 ± 1.2	14.5 ± 1.2	10.5 ± 3.6
Symbols	With CI	8.3 ± 1.1	10.3 ± 1.2	9.5 ± 1.2	9.4 ± 1.0
HOTV	Isolated	7.4 ± 1.2	5.9 ± 1.2	6.5 ± 1.1	6.6 ± 0.8
	With CI	6.2 ± 1.3	7.3 ± 1.2	6.6 ± 1.3	6.7 ± 0.6
	Crowded	7.4 ± 1.0	8.3 ± 1.5	8.6 ± 1.1	7.8 ± 0.7
Average		8.1 ± 1.4	8.3 ± 1.5	10.1 ± 3.5	8.8 ± 2.4

Luminance modulated compared to standard luminance tests

The difference between L and LM acuities was minimal in 3-4 year olds (0.017 ± 0.009 logMAR) which increased with age to 0.088 ± 0.024 logMAR with adults. This may indicate that the level of internal neural noise is higher in children, thereby reducing the effect of noise within the stimuli. It has previously been suggested that internal neural noise is higher in amblyopes (Pelli, Levi and Chung, 2004). As seen below for a sample of binocularly abnormal adults, the difference between L and LM acuities was similar to that of normal adults in the non-amblyopic eye (at 0.084 ± 0.008 logMAR) but indeed smaller in the amblyopic eye (at 0.055 ± 0.010 logMAR), like that in normal developing children.

4.2 Use of L, LM and CM stimuli in binocularly abnormal adults

Crowded CM stimuli are potentially more valuable to use for detecting amblyopia earlier because amblyopes show a larger detection loss (Wong et al., 2005) and greater contour interaction and crowding effects (Chung et al., 2007; Hairol et al., 2013) for these stimuli, than for L/LM stimuli. In addition, CM stimuli are thought to be processed in more binocular neural areas, so that binocularly abnormal visual systems might be more susceptible to revealing that loss (Wong et al., 2005; Hairol et al., 2013). Amblyopes and stereo-blind individuals have clear deficits in binocularity and strabismic amblyopes show exaggerated crowding compared to that measured in normal adults (e.g., Levi and Klein, 1985; Hess et al., 2001). In this study, it has been found that crowding is also exaggerated in normal young children, although CM optotypes did not offer any advantage over standard L/LM optotypes in revealing this crowding. This does not rule out their potential value in binocularly abnormal children, although this will need to be investigated in a future study. Since amblyopia is due to abnormal binocular development, visual acuity measured with CM optotypes may still offer improved sensitivity.

To gain some insight into the nature of CM processing in binocularly abnormal visual systems, visual acuities for a sample of adults with abnormal binocular vision (n=19; see Tables 4.2, 4.3 and 4.4) were tested using the L, LM and CM optotypes, the same configural arrangements, and the same staircase paradigm used in Experiment 2. Details of these participants are given in Tables 4.2, 4.3 and 4.4. Participants are grouped into stereo-blind non-amblyopic, anisometropic amblyopic or strabismic amblyopic groups. Some strabismic amblyopes also had anisometropia, however due to the presence of micro-strabismus, they were classified as strabismic amblyopes.

Table 4.2: *Details of stereo-blind (SB), non-amblyopic participants who had treatment for amblyopia as a child. They have reduced stereoacuity, but have <0.2 logMAR inter-ocular difference in visual acuity so are no longer amblyopic.*

	Type	Prescription	VA	Fixation	Patching	Surgery	Specs	Cover Test	Stereo	BCS
JMC	SB	**R:**-3.50/-2.00$\times$12	-0.04	Alternating fixation,	5yo BE	18mo, 3yo,	From	10ΔLSOT	>480”	-4.50
		L:-1.00/-3.00$\times$171	-0.06	RE preference		3y & 18yo	5yo	8ΔLHYP		-2.50
NP	SB	**R:** +6.00/-0.25$\times$175	-0.20	**R:** Unsteady central	5yo	None	From	13ΔRSOT	>480”	+5.875
		L: +5.25/-1.50$\times$179	-0.20	**L:** Normal			5yo			+4.50
PML	SB	**R:** -3.00DS	0.1	**R:** 0.2 deg nasal	2-4yo	1.5 &	From	8ΔRSOT	>480”	-3.00
		L: -1.50/-0.25$\times$170	-0.02	**L:** Steady eccentric		17yo	1.5yo			-1.625
RH	SB	**R:**+1.25/-1.25$\times$120	-0.2	**R:**Central	5yo	5yo	From	LE 20ΔEST	>480	+0.625
		L:+3.50/-2.00$\times$120	-0.1	**L:**0.38 deg temp			13mo	30ΔHYPO		+2.50
AE	SB	**R:** +2.25/-0.50$\times$90	-0.10	BE Central	3yo	3oy	From	8ΔRSOT	>480”	+2.00
		L: +2.25/-1.00$\times$95	-0.14	steady			3yo			+1.75
AW	SB	**R:** +6.50/-2.75$\times$164	-0.16	**R:** Central steady	Infant	None	None	6ΔLSOT	>480”	+5.125
		L: +6.25/-3.25$\times$3	-0.08	**L:** 0.30 deg nas	school					+4.625
JaB	SB	**R:** ∞/-0.50$\times$175	-0.14	Alternating XOT	5yo	5yo	Until	35–40ΔIN	>480”	-0.25
		L:-0.25/-0.25$\times$90	-0.14				8y			-0.375

Table 4.3: *Details of an amblyopic participant with pure ansiometropia (AA).*

	Type	Prescription	VA	Fixation	Patching	Surgery	Specs	Cover Test	Stereo	BCS
LC	Aniso	**R:** +0.25/-0.75$\times$5	-0.1	**BE:** Central steady	5yo	None	From	NMD	120”	-0.125
		L: +0.50/-4.50$\times$4	0.26				5yo			-1.75

Table 4.4: *Details of amblyopic participants (≥0.2 logMAR inter-ocular difference in visual acuity) associated with strabismus or micro-strabismus (SA).*

	Type	**Prescription**	**VA**	**Fixation**	**Patching**	**Surgery**	**Specs**	**Cover Test**	**Stereo**	**BCS**
AH	Strab	**R:** -3.25DS **L:** -1.50DS	0.16 -0.04	**R:** 1.8 deg sup **L:** 1 deg sup temp	5yo	7yo	5yo	20ΔRXOT 10ΔHYP	>480”	-3.25 -1.50
AR	Strab	**R:** +2.25/ -0.50×5 **L:** +5.00/-0.75×22	-0.18 0.02	**R:** Central steady **L:** Temp. steady	None	None	From 14yo	NMD	120”	+2.00 +4.625
ChM	Strab	**R:** +3.00/-2.25×11 **L:** +6.25/-3.25×3	-0.08 0.40	**R:** Central steady **L:** 0.52 deg nas	3yo	None	From 4yo	26ΔLSOT	>480”	+1.875 +4.625
JB	Strab	**R:** +4.25/-0.50×80 **L:** +1.00/-1.00×100	0.40 -0.04	**R:** 0.86 deg sup nas **L:** Central steady	5yo	6yo	7-11yo	6ΔSOP	>480”	+4.00 +0.50
MTW	Strab	**R:** +5.75/-1.50×145 **L:** $+4.00/-1.50\times70$	0.5 0.0	**R:** Steady eccentric **L:** Normal	3–7yo	None	From 3yo	4ΔSOT	>480”	+5.00 +3.25
DM	Strab	**R:** +2.25/-1.75×162 **L:** +3.00/-2.25×7	-0.16 0.04	**R:** Central steady **L:** 0.58 deg inf temp	4y	None	4yo	7ΔXOP	120”	+1.375 +1.875
FD	Strab	**R:** -1.00/-1.00×180 **L:**-0.50/-0.75×140	0.44 -0.08	**R:**0.4 deg nasal **L:** Central steady	3-8yo	8yo	29yo	REST	>480	-1.50 -0.875
KB	Strab	**R:** +4.50/-0.50×81 **L:** +4.25/-1.25×130	0.36 -0.06	**R:** Unsteady eccentric **L:**Central steady	Infant school	3yo	3yo	4ΔRSOT	240”	+4.25 +3.50
NiS	Strab	**R:** +8.50/-2.25×5 **L:** +8.25/-2.50×3	0.12 -0.20	**R:** Eccentric **L:** Normal	None	None	From 4yo	PHI XOP	240”	+7.375 +7.00
RC	Strab	**R:** +1.75/-0.25×100 **L:** +2.00/-0.25×80	0.06 0.34	**R:** 0.4 deg nasal **L:** Central steady	Infant school	6yo	From 6yo	NMD	>480”	+1.625 +1.875
SR	Strab	**R:** +5.00/-2.00×165 **L:** +4.00DS	-0.10 0.50	**R:** Central steady **L:** Central steady	Infant school	6yo	From 6yo	NMD	>480”	+4.00 +4.00

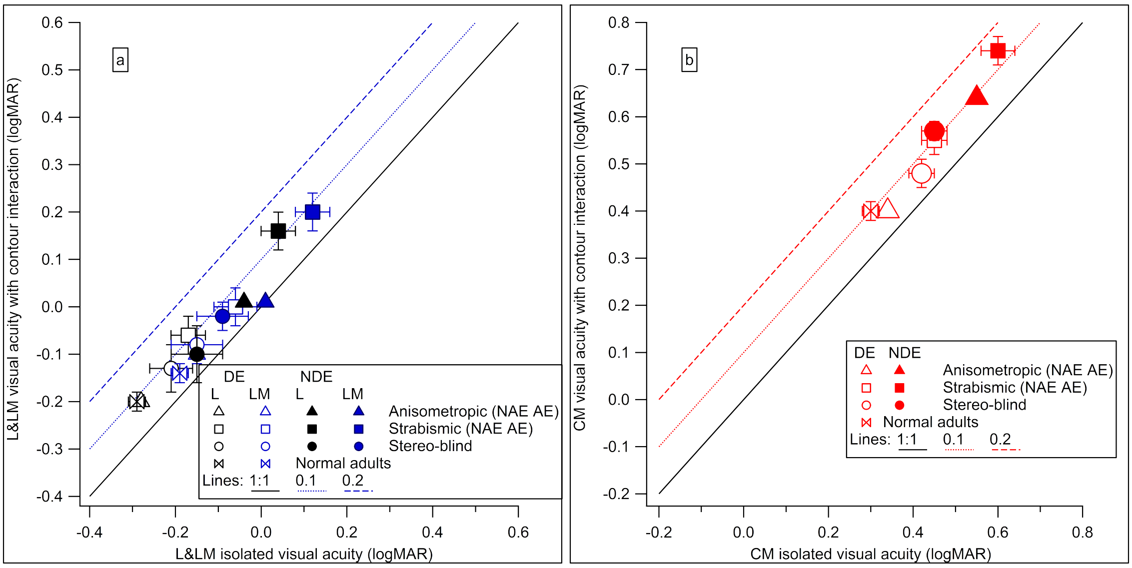


Figure 4.4: *Isolated visual acuities plotted against visual acuities measured with contour interaction features for stereo-blind, amblyopic and normal adults with (a) L and LM stimuli (left) and (b) CM stimuli (right).*

Contour interaction effects are shown in Figures 4.4a and 4.4b. These are similar again to the results of normal healthy children and adults revealing around 0.1 logMAR detrimental effect on visual acuity, although they are slightly greater for CM stimuli (on average 0.14 ± 0.02 logMAR effect), for eyes with strabismic amblyopia. This means that clinically, use of a box around CM optotypes would slightly enhance interocular visual acuity differences for this group of participants.

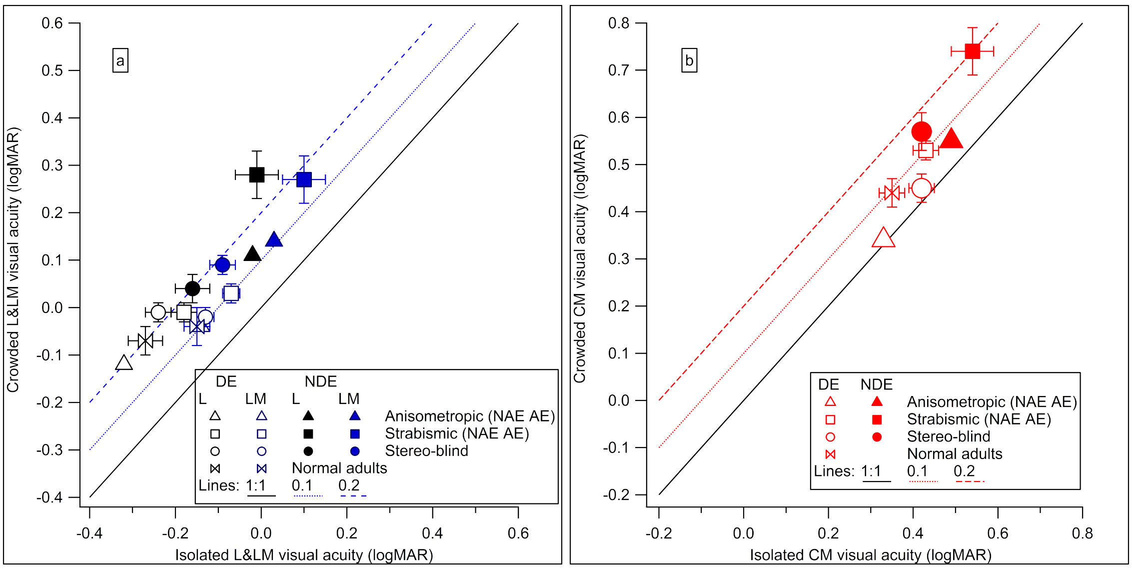


Figure 4.5: *Isolated visual acuities plotted against visual acuities measured with crowding features for stereo-blind, amblyopic and normal adults with (a) L and LM stimuli (left) and (b) CM stimuli (right).*

When letters surround letters (i.e., a crowded format), the difference between eyes is enhanced relative to contour interaction effects for L/LM optotypes (see Figure 4.5). Interestingly, for CM optotypes, crowding by letters was no stronger (and sometimes weaker) than contour interaction effects measured with a box (on average reducing by 0.021 ± 0.013 logMAR), for normal healthy adults. However, for binocularly abnormal participants, particularly those with strabismic amblyopia, crowded CM stimuli produce stronger effects (increasing on average by 0.057 ± 0.02 logMAR). Enhanced crowding for CM stimuli, above that provided by contour interaction, therefore appears to be diagnostic of a binocular anomaly. These findings are more clearly demonstrated in Figure 4.6. It is interesting that a similar level of crowding enhancement (above contour interaction) for CM stimuli is also found for 3 to 4 year old children (increasing on average by 0.061 ± 0.030 logMAR).

Further work would be needed to determine whether similar effects extend to purely anisometropic amblyopes, as there is only one such participant in this sample, however unlike in strabismic amblyopia, evidence in the classical (Flom, Weymouth and Kahneman, 1963) and recent (Formankiewicz and Waugh, 2013; Song et al., 2014) literature does not support the notion of exaggerated crowding in anisometropic amblyopia.

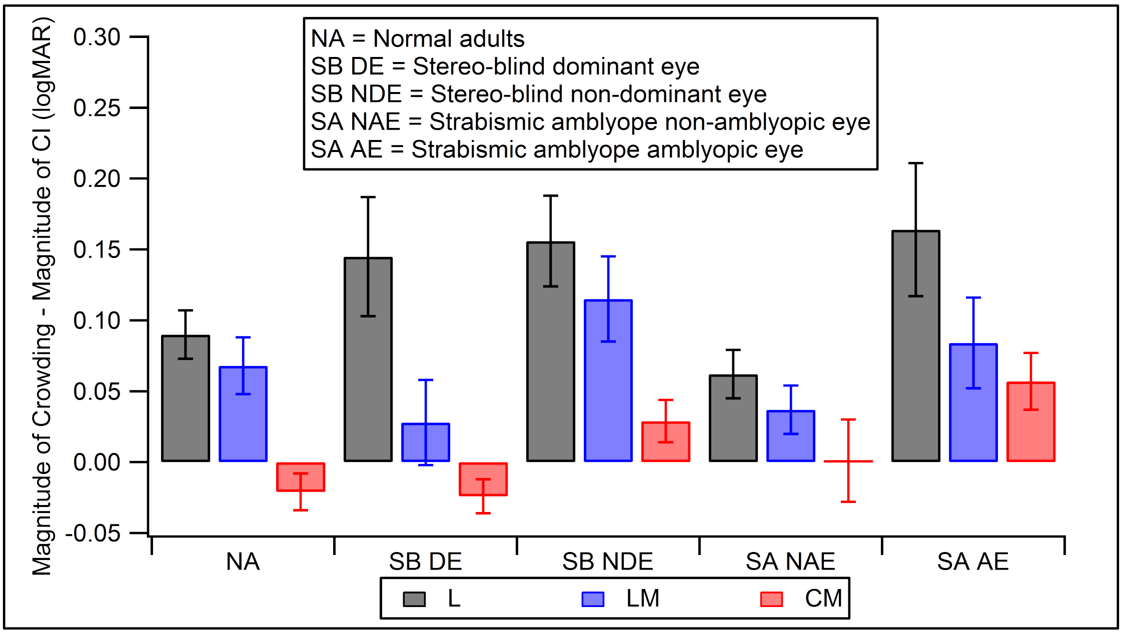


Figure 4.6: *The difference in magnitude of contour interaction and crowding for normal and binocularly anomalous adults.*

4.3 Equivalent age of binocularly abnormal adults for L, LM and CM acuity optotypes

Visual acuity for CM optotypes reached adult levels at a later age and developed at a slower rate in young children. Visual acuities for isolated optotypes, optotypes surrounded by a box, and letters surrounded by letters were compared for each participant in the binocularly abnormal group with those for children aged 3 to 16 years. Using the equations for two line fits of Experiment 2, the equivalent age for each non-dominant/amblyopic eye (n=19) was determined based on their visual acuities for each stimulus type (L, LM and CM). The equivalent age was then plotted against the age at which treatment was initiated in Figure 4.7.

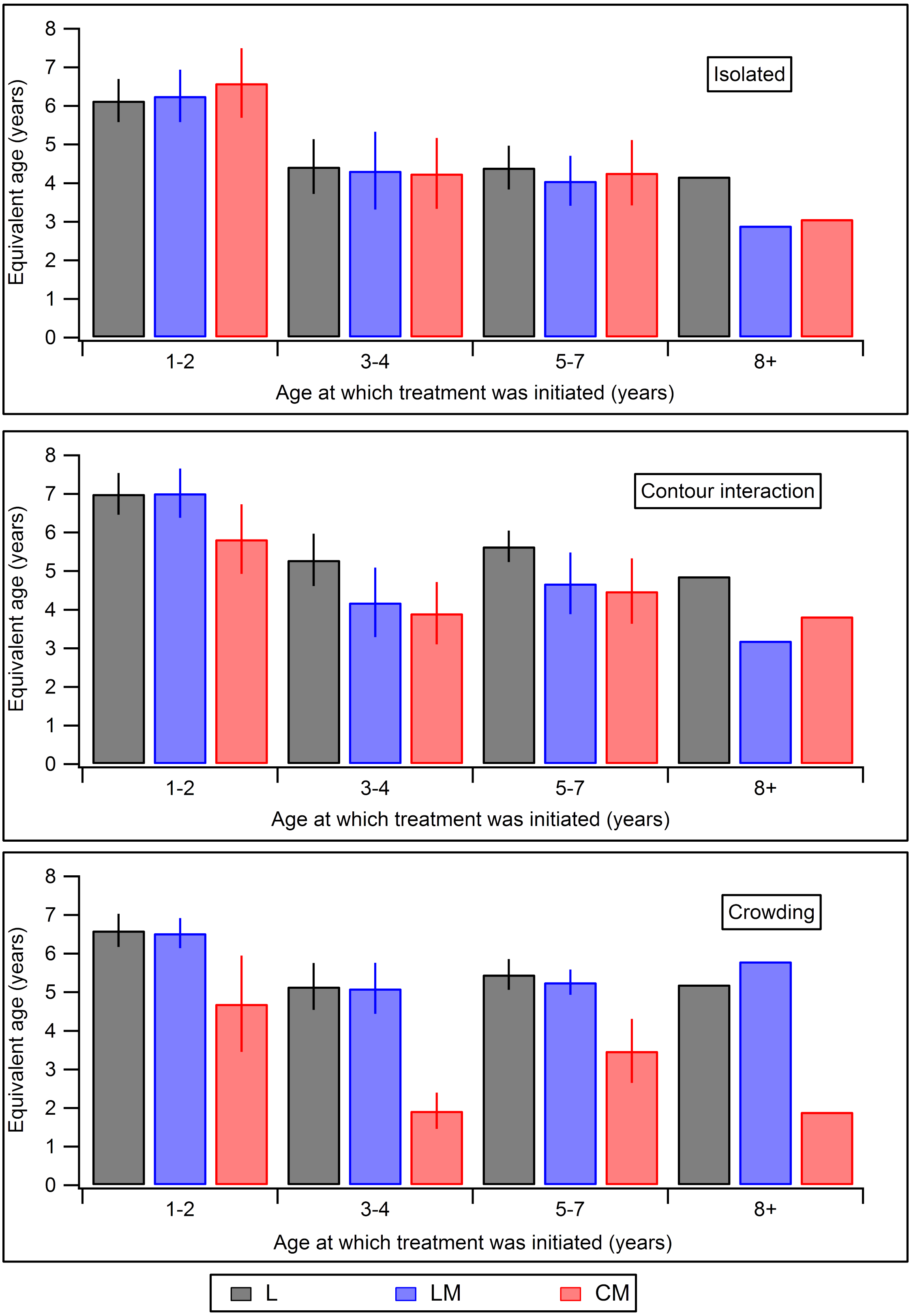


Figure 4.7: *The equivalent age for binocularly abnormal participants (based on visual acuities from two-line-fits to data from normal children) plotted against age at which amblopia treatment was initiated (Tables 4.2, 4.4 and 4.3) with isolated optotypes (top), contour interaction features (middle) and crowding features (bottom).*

If only isolated acuity is measured, all three stimulus types predict a similar equivalent age. For acuities measured with contour interaction, equivalent ages for CM stimuli are on average, slightly younger than those estimated for L and LM stimuli. The largest difference between stimulus types is revealed for crowded letter arrangements. In this case, CM stimuli estimate much younger equivalent ages for the binocularly abnormal participants.

This result supports the notion that CM stimuli are more sensitive to abnormal binocularity and will detect it at an earlier stage. As earlier treatment has been demonstrated to lead to more successful treatment outcomes (Flynn et al., 1998, 1999), use of crowded CM optotypes might be of potential value.

4.4 Implications of Results

The results in this thesis indicate that the placement of features surrounding the target optotype would provide more consistent contour interaction if they were specified in stroke widths instead of optotype widths as is most commonly used currently. To maximise the effect of surrounding features, a decrease in the target-flanker separation on visual acuity tests would be beneficial. Steeper slopes of the underlying psychometric functions, and thereby increased sensitivity, are produced by placing contour interaction or crowding features near to one stroke width away. The peak contour interaction and crowding effect is also close to one stroke width target-flanker separation.

The potential usefulness of a contrast-modulated noise (CM) visual acuity test is indicated by the results in this thesis. The magnitude of contour interaction is smaller than that of crowding with L and LM, but not with CM, stimuli in normal adults and older children, i.e., in a mature, binocularly normal visual system. This is not the case for very young children or binocularly anomalous adults. A comparison of 'equivalent ages' for binocularly abnormal adults finds that CM crowded acuity predicts an earlier arrest of normal development, than do L or LM crowded, or any of the isolated optotype acuities. These findings mean that if for a patient, crowding measured with CM stimuli is greater than the contour interaction measured, then that patient's visual system is very likely to be immature or binocularly anomalous.

4.5 Future work

Acuity measured depends the test optotype (Kay, Lea, HOTV) used to measure it, but the dependence may not be the same for young children and adults. Lea symbols seemed to provide slightly higher acuities across all age groups. Kay pictures estimate lower acuities than Lea symbols for all age groups. Confidence with letters may be different for different age groups and so should be used with caution in young children. The results of this study indicate that there is potential for a crowded CM test to be more sensitive to amblyopia. However, to investigate this fully it will be necessary to test amblyopic children and a wider range of amblyopic adults.

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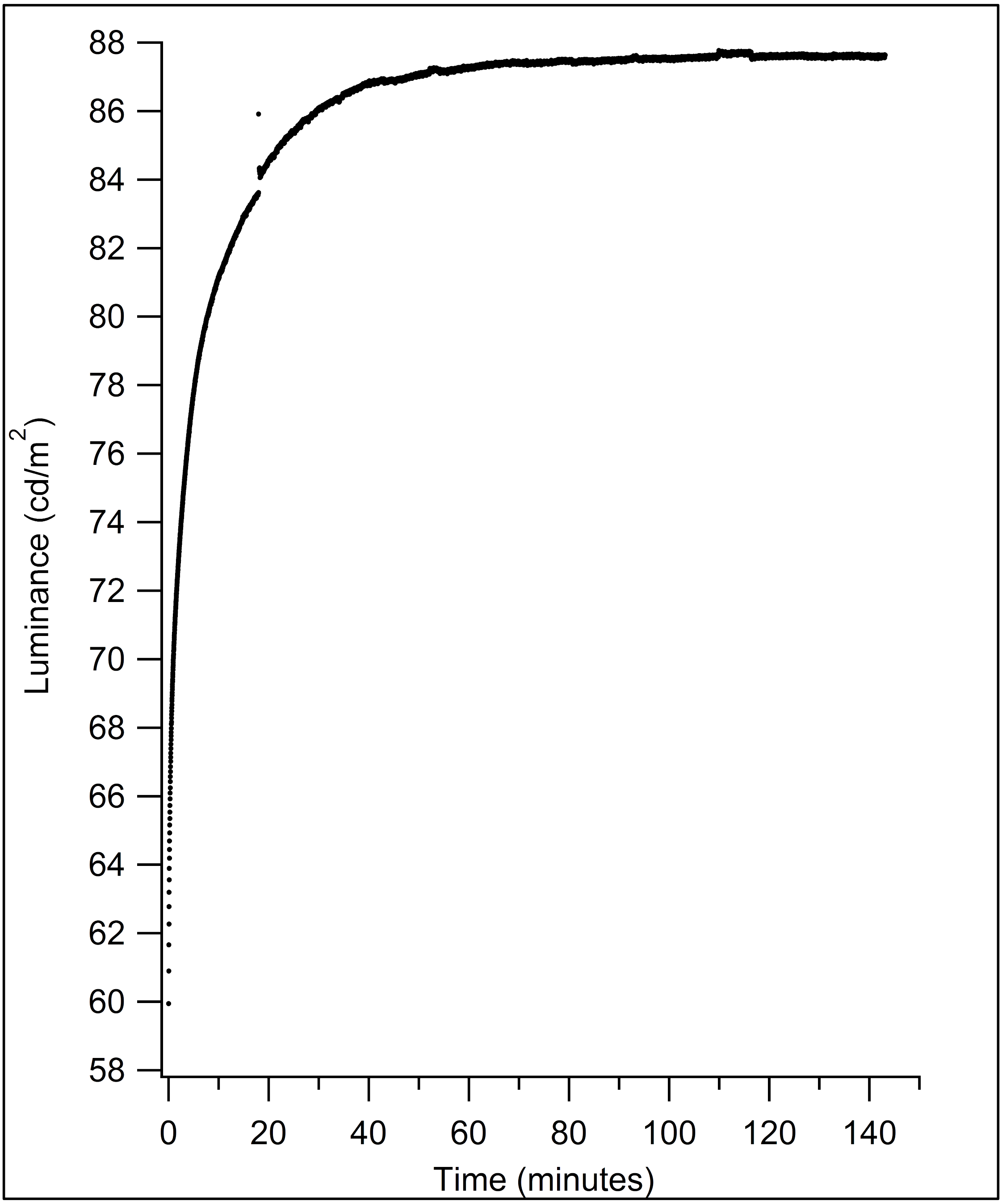
Appendix A: Monitor warm-up



Appendix B: Measurements of Lea Symbols

LogMAR size	Optotype	Measured height	Measured stroke width	Height difference	Stroke width difference
0.6	Square	20.5mm	3mm	-1.0mm	
	Apple	21.0mm	3mm	-0.5mm	
	Circle	22.0mm	3mm	+0.5mm	
	House	21.5mm	3mm		
	Square	20.5mm	3mm	-1.0mm	
	Square	20.5mm	3mm	-1.0mm	
	Apple	21.0mm	3mm	-0.5mm	
	Circle	22.0mm	2.5mm	+0.5mm	-0.5mm
	House	21.5mm	3.5mm		+0.5mm
0.5	House	17.0mm	2mm		
	Square	16.5mm	2mm	-0.5mm	
	Apple	17.0mm	2mm		
	Square	16.5mm	2mm	-0.5mm	
	Circle	17.5mm	2mm	+0.5mm	
	Apple	17.0mm	2mm		
	Circle	17.0mm	2mm		
	Square	16.0mm	2mm	-1.0mm	
	House	17mm	2.5mm		+0.5mm

0.4	Apple	13.5mm	2mm		+0.5mm
	Circle	14.0mm	1.5mm	+0.5mm	
	Square	13.0mm	1.5mm	-0.5mm	
	Apple	13.0mm	2mm	-0.5mm	+0.5mm
	House	13.5mm	2mm		+0.5mm
	Square	13.0mm	1.5mm	-0.5mm	
	Apple	13.5mm	1.5mm		
	Circle	14mm	1.5mm	+0.5mm	
	House	13.5mm	2mm		+0.5mm
0.3	House	10.5mm	1mm		
	Circle	11mm	1mm	+0.5mm	
	Apple	10.5mm	1mm		
	Square	10.5mm	1mm		
	Apple	10.5mm	1mm		
	Circle	11.0mm	1mm	+0.5mm	
	Square	10.0mm	1mm	-0.5mm	
	House	10.5mm	1mm		
	Apple	8.5mm	1mm		
0.2	Circle	9.0mm	1mm	+0.5mm	
	Apple	8.5mm	1mm		
	House	8.5mm	1mm		
	Square	8.0mm	1mm	-0.5mm	
	Circle	8.5mm	1mm		
	Square	8.0mm	1mm	-0.5mm	
	Circle	8.5mm	1mm		
	House	8.5mm	1mm		
	Apple	8.5mm	1mm		

0.1	Apple	6.5mm	0.5mm	
	Circle	6.5mm	0.5mm	
	Apple	6.5mm	0.5mm	
	House	6.5mm	0.5mm	
	Square	6.5mm	0.5mm	
	Circle	7.0mm	0.5mm	+0.5mm
	Square	6.5mm	0.5mm	
	Apple	6.5mm	0.5mm	
	House	6.5mm	0.5mm	
0.0	Square	5.0mm	0.5mm	
	Apple	5.0mm	0.5mm	
	House	5.0mm	0.5mm	
	Circle	5.5mm	0.5mm	
-0.1	Circle	4.5mm	0.5mm	+0.5mm
	House	4.0mm	0.5mm	
	Square	4.0mm	0.5mm	
	Apple	4.0mm	0.5mm	

Appendix C: Matching cards

Kay Pictures:

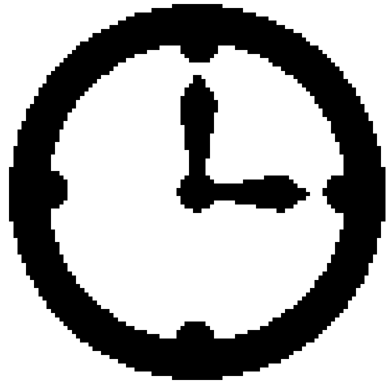
- Standard luminance
- Luminance-modulated
- Contrast-modulated

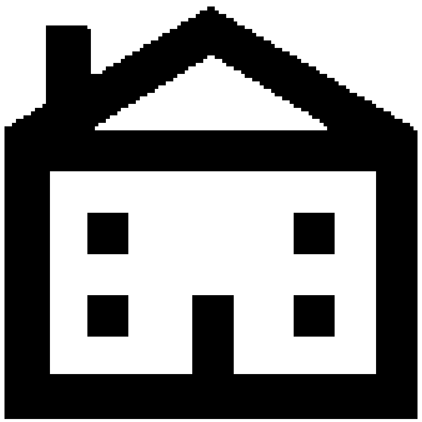
Lea Symbols:

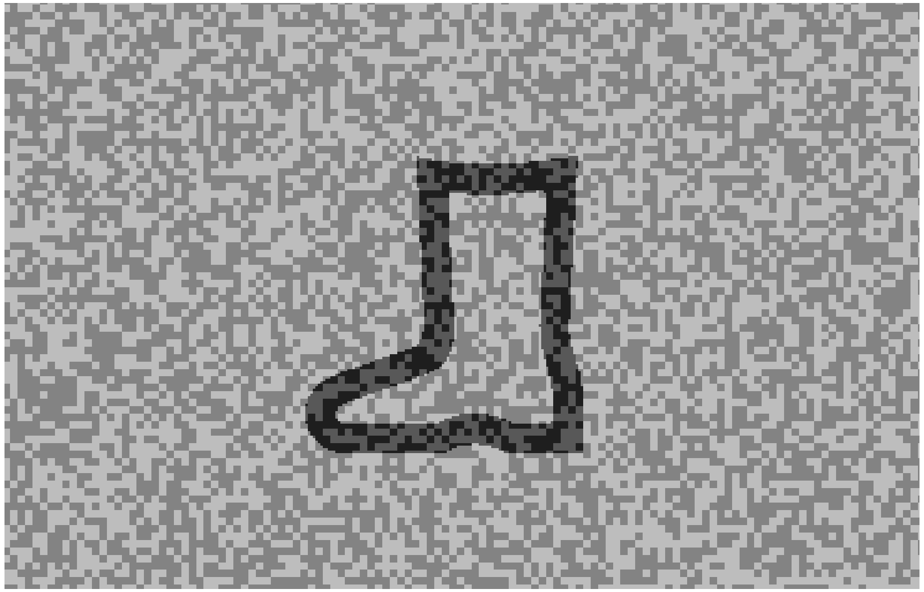
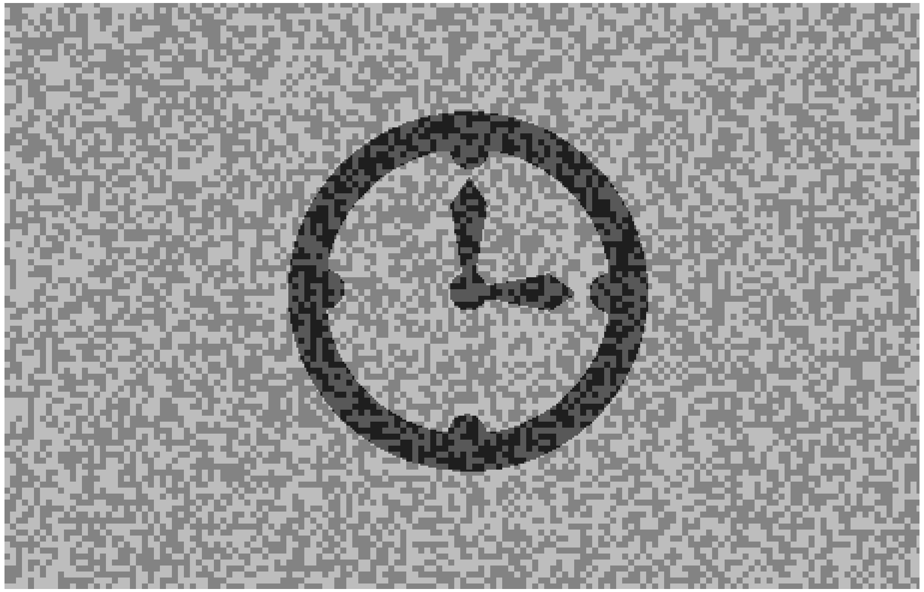
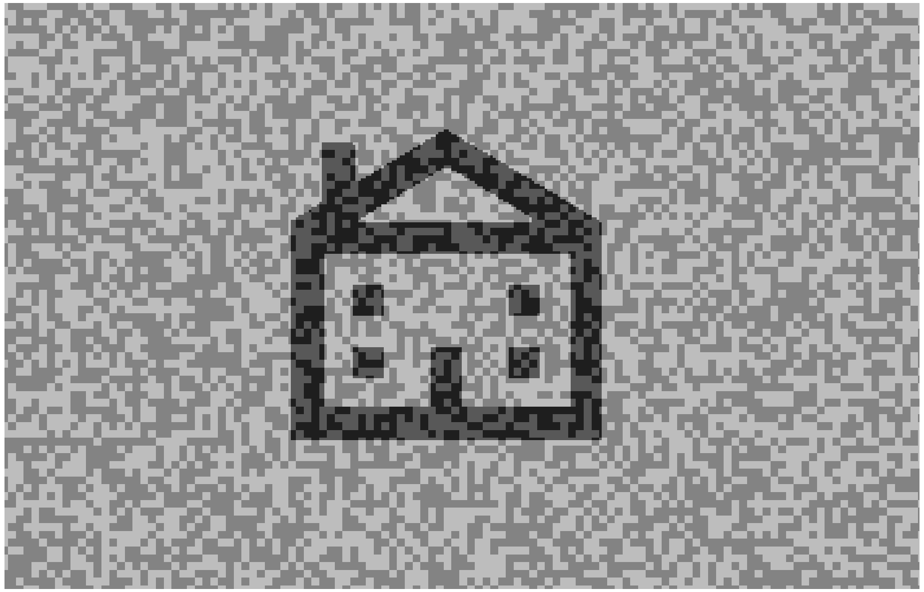
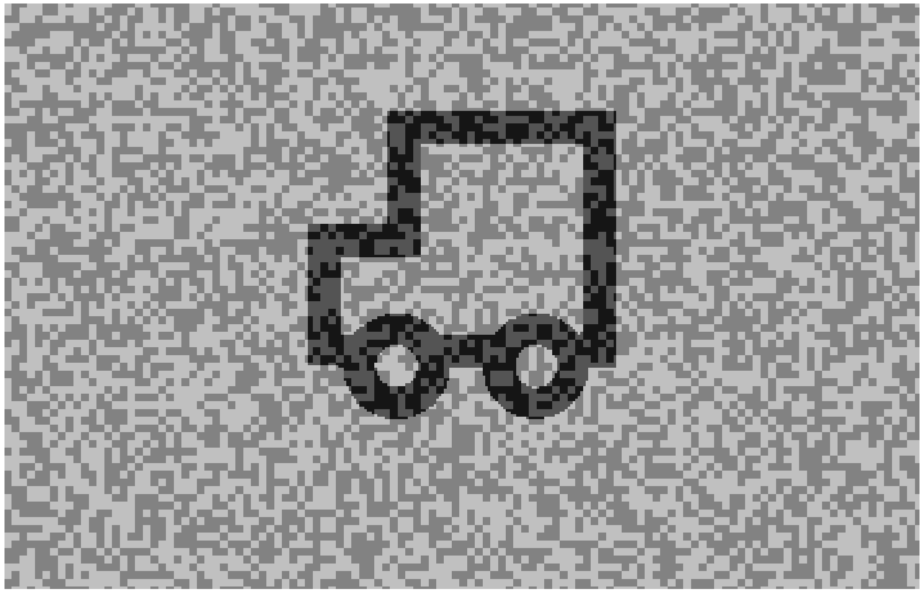
- Standard luminance
- Luminance-modulated
- Contrast-modulated

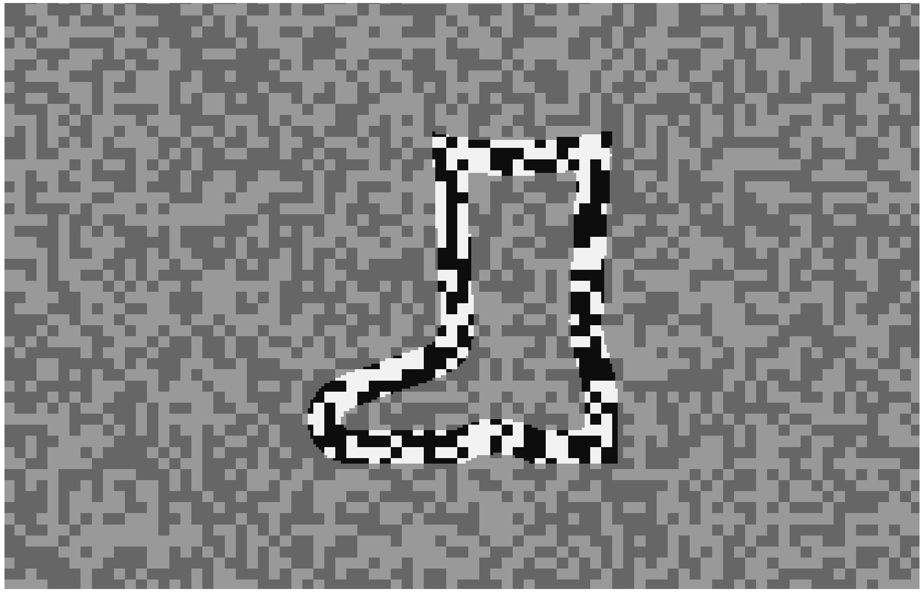
HOTV and Cambridge Crowding Cards:

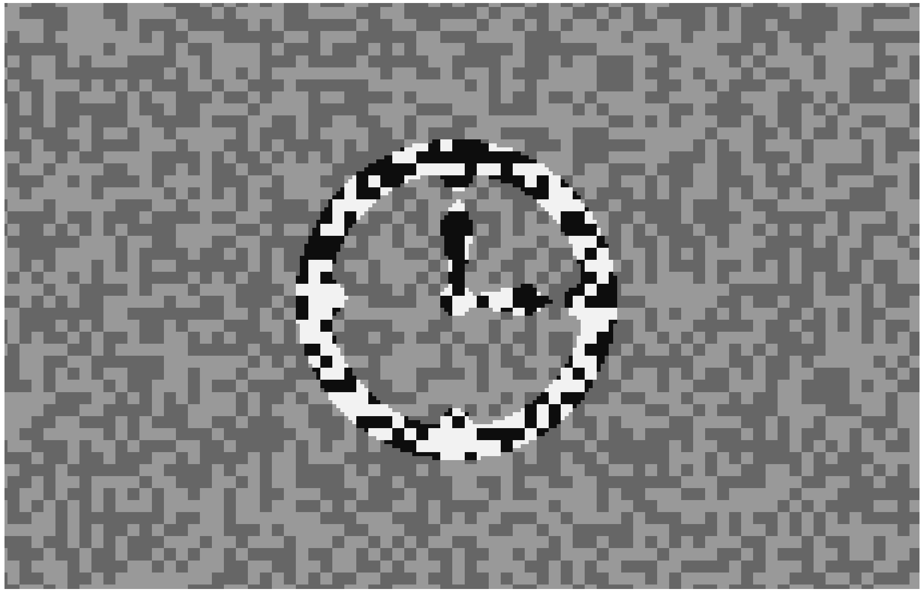
- Standard luminance
- Luminance-modulated
- Contrast-modulated

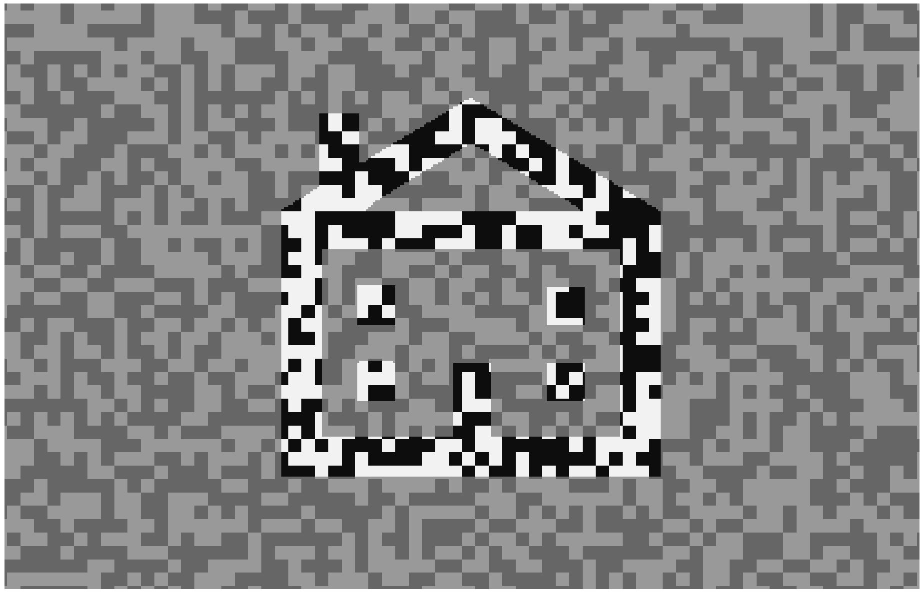


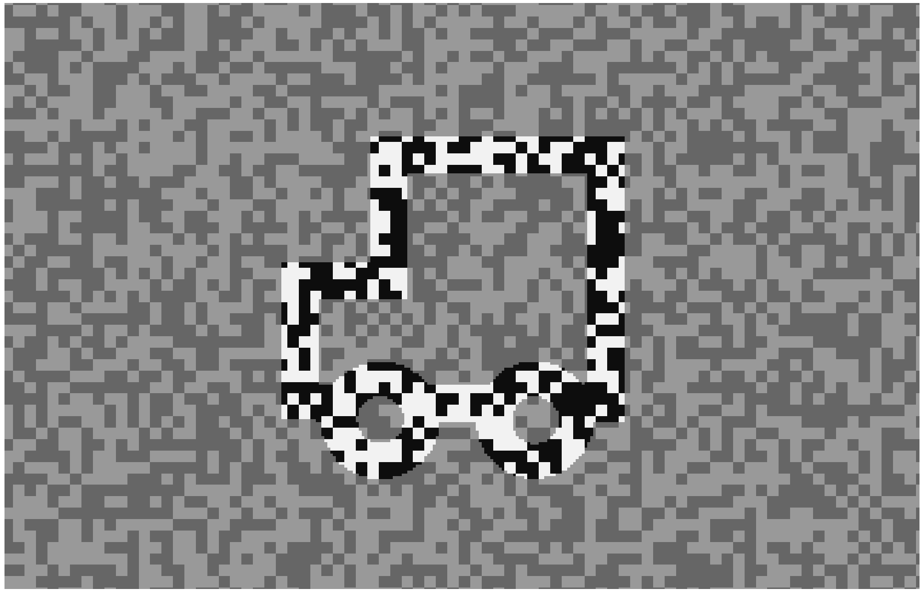


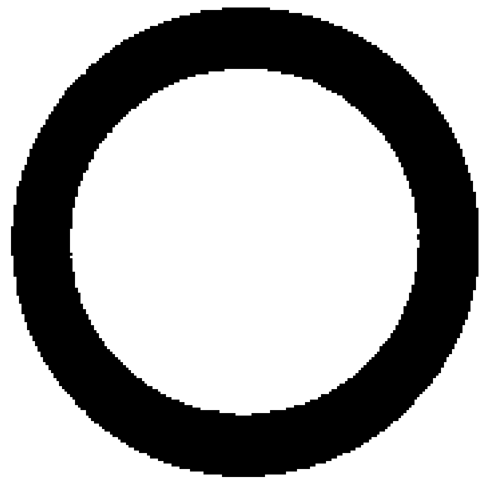





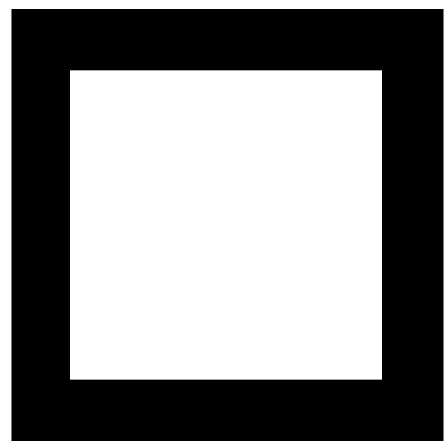


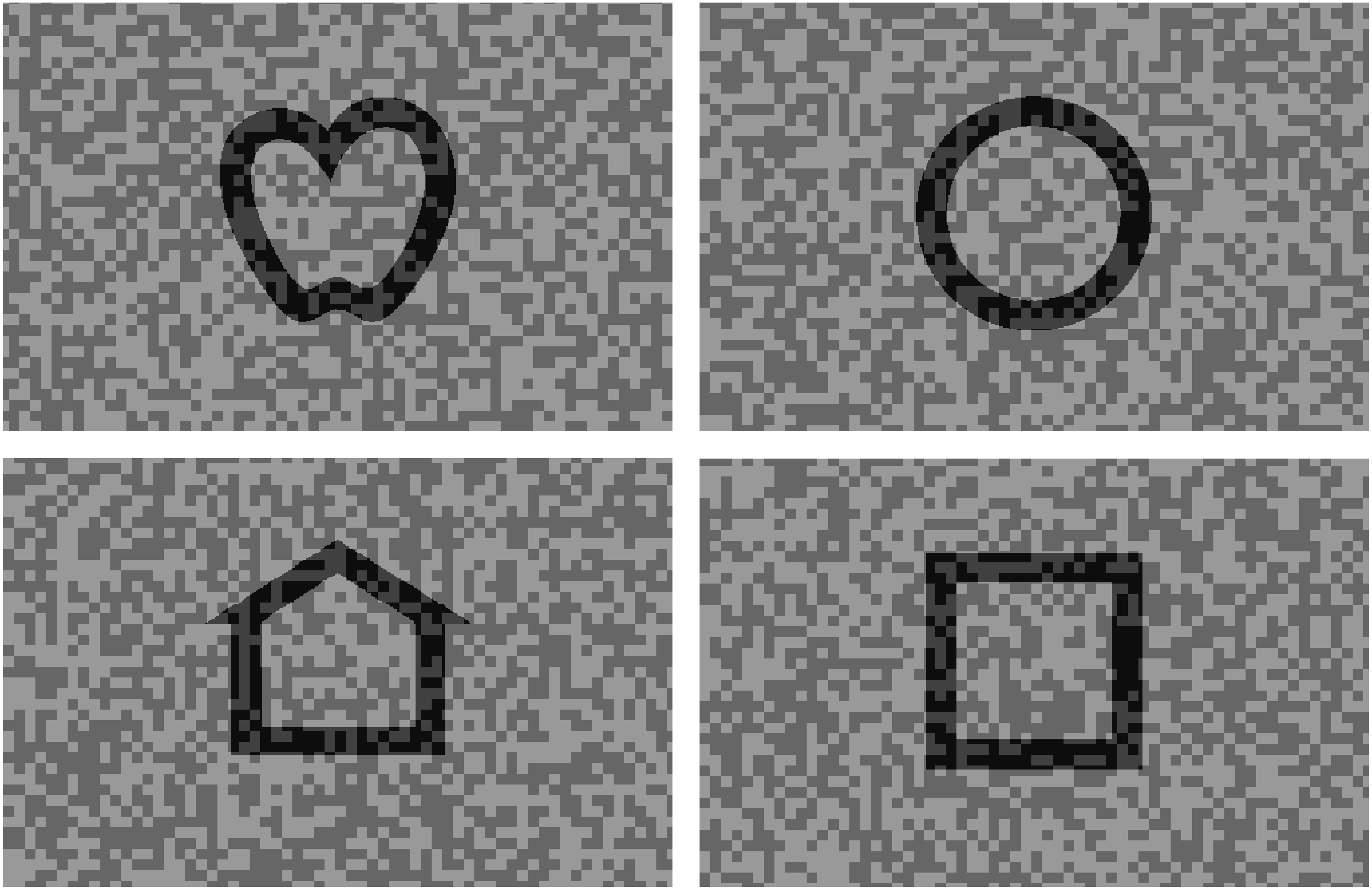


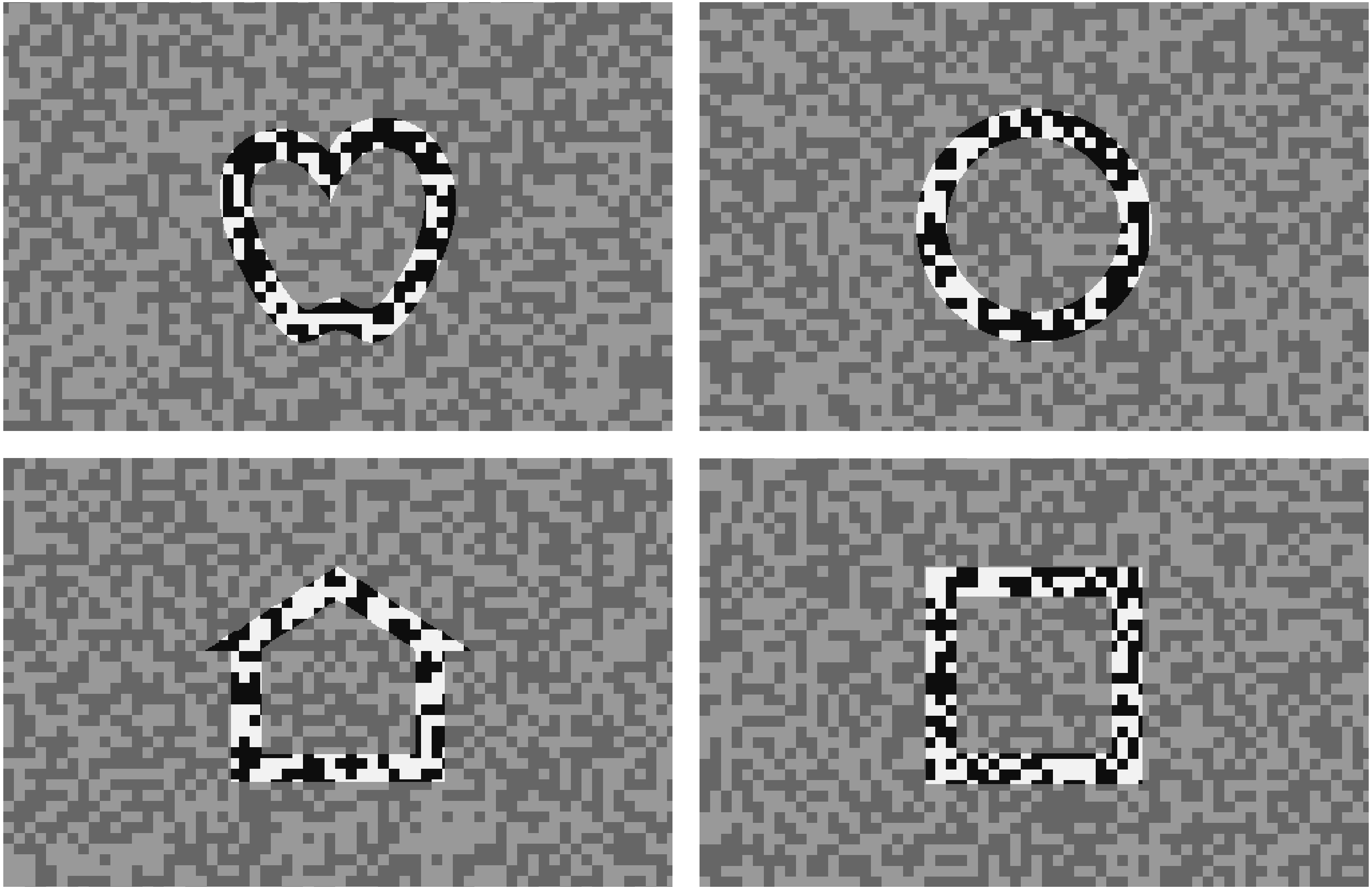












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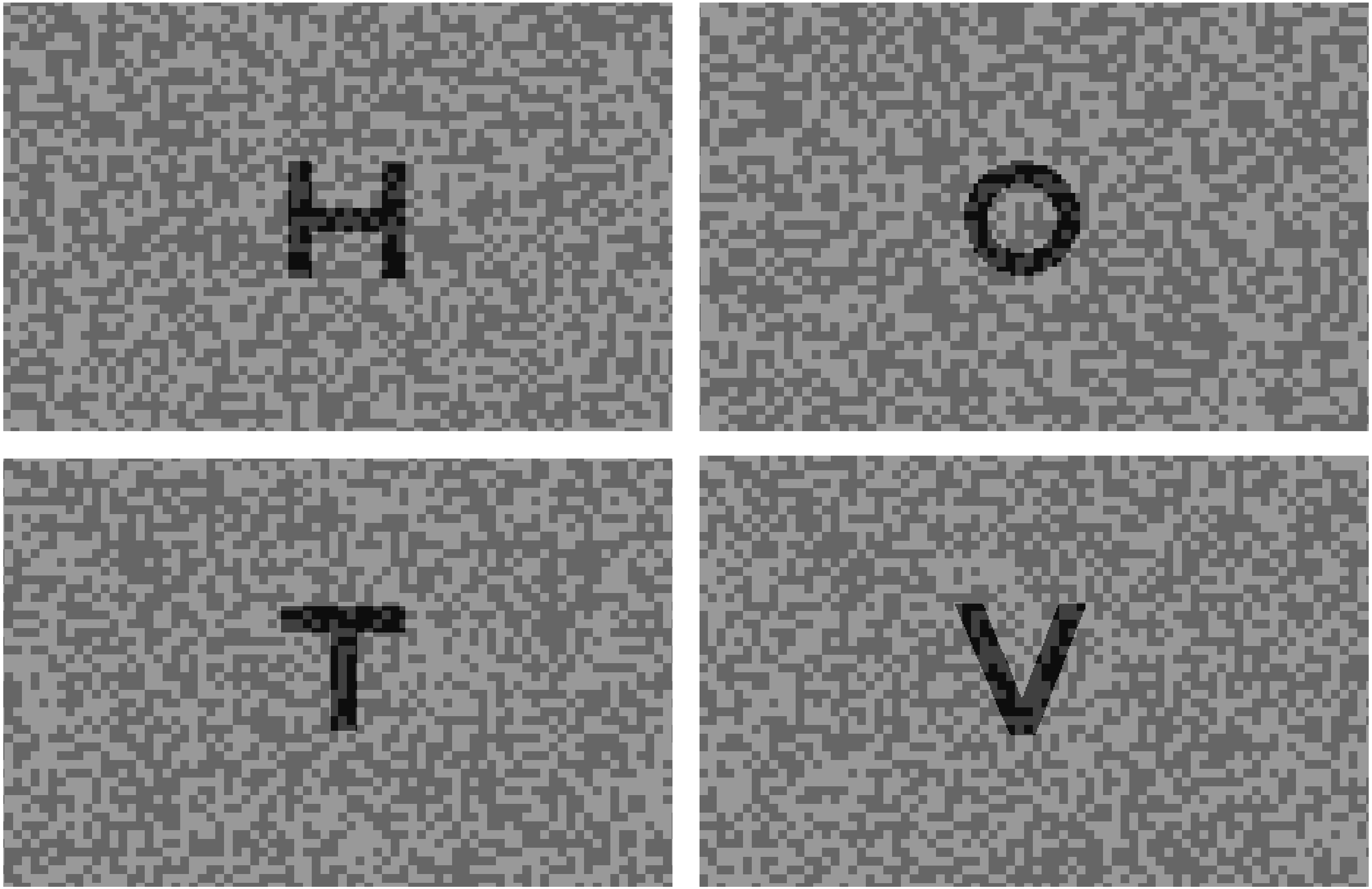
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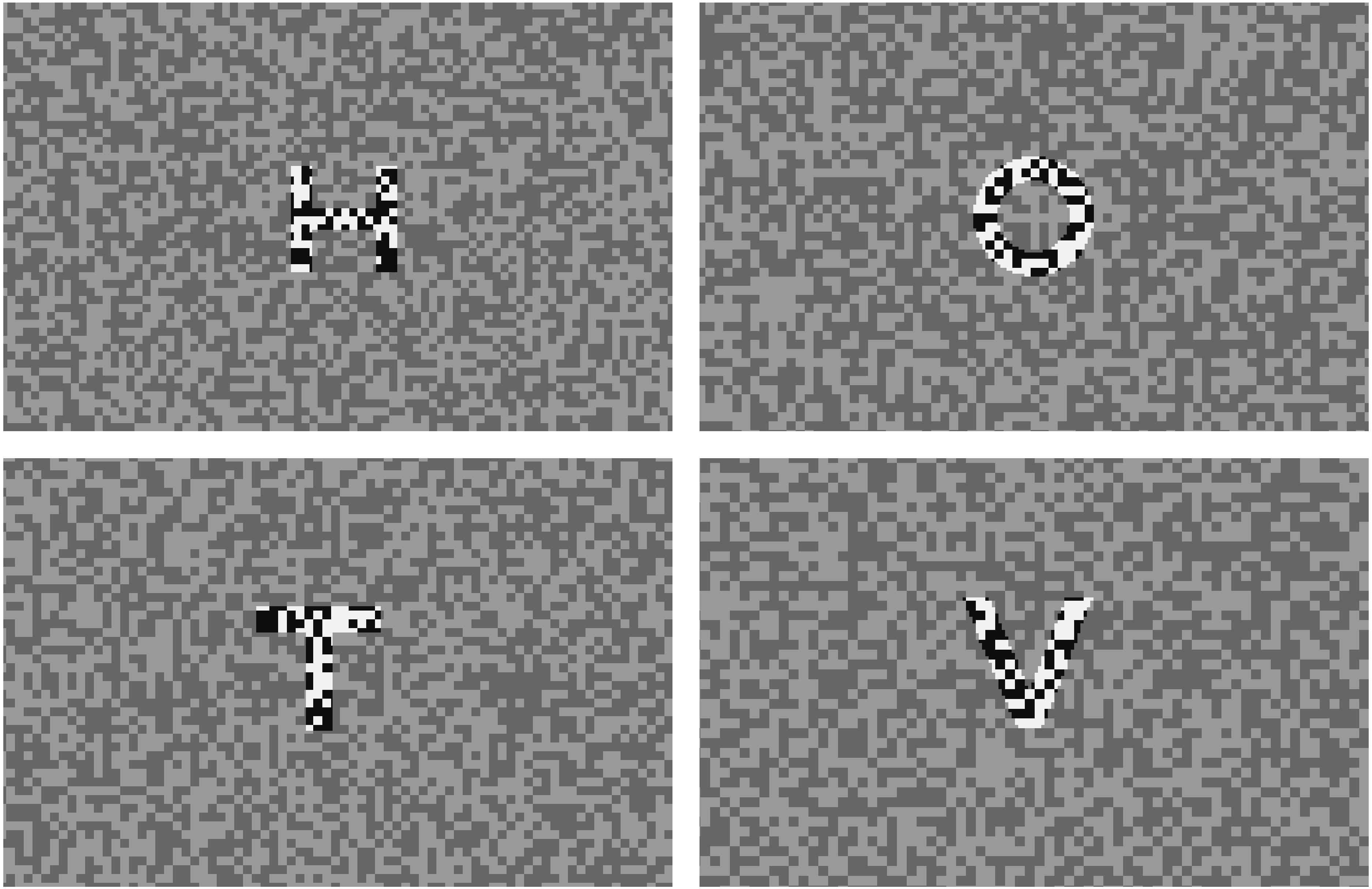
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Appendix D: Participant information sheets and consent forms

- Advert
- Participant information sheet for children
- Parent information sheet
- Consent form

PARTICIPANTS REQUIRED!

We are carrying out research into children's vision and are hoping to develop a better vision chart so that we can detect Amblyopia (also known as "Lazy Eye") as early as possible. We are looking for participants aged from 3 to 16 years old, particularly those aged from 3 to 11 years old. All children are welcome, including those who wear glasses.

The research will take place within the Evelyn Trust Anglia Vision Suite at Anglia Ruskin University and will last approximately 30 minutes.

If you would like more information, please contact Sarah Lalor:

- sarah.lalor@anglia.ac.uk
- 01223 363271 ext 2688

Sarah Lalor—Children's vision charts study
sarah.lalor@anglia.ac.uk
01223 363271 ext 2688

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Information Sheet

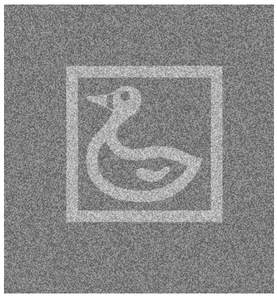
Hello!

We want to learn more about how children see. We would like you to help us.

We will ask you to look at a computer screen that looks like this:

It will have something like this on it:

Some of them will look a bit like this:



You will be asked to wear a soft eye patch over one eye. It will look a bit like this:

Or if you like you can wear some special glasses to cover one of your eyes. They may look a bit like this:

You will be asked to say what you think you see on the screen. You will be shown pictures of what you might see before you start.

PARENTS INFORMATION SHEET

Title of project: What is the most effective visual acuity chart for children?

Your child is invited to participate in a study to find out how children of different ages see letters or symbols that are seen because of changes in luminance, contrast or texture. It is thought that the visual processing of some types of images may be more adversely affected in visual disorders such as amblyopia (also known as “lazy eye”) than with traditional black letters or symbols on a white background.

The aim of this study is to measure vision using standard and non-standard letters and symbols for children of different ages. This will help us to decide whether a more effective clinical chart could be created using these non-standard letters and symbols.

A more effective clinical chart could help to improve the detection of anomalous visual disorders in children. In cases such as amblyopia (“lazy eye”), early detection enables early treatment, which leads to a much more favourable outcome (i.e. good vision in each eye and better binocularity).

This research is being conducted by Miss Sarah Lalor under the direct supervision of Dr Sarah J Waugh, along with her research team, Anglia Vision Research, within the Department of Vision and Hearing Sciences at Anglia Ruskin University. Dr Sarah Waugh has been a consultant optometrist in the paediatric eye clinic at Addenbrookes Hospital, Cambridge for the last eight years.

The study will be conducted in the Evelyn Trust Anglia Vision Suite, which is on the fourth floor of Coslett on the attached map of Anglia Ruskin University, East Road Campus, Cambridge.

The results of this study may be reported at scientific meetings, may appear in scientific publications and may be used in a doctoral thesis, but your child will not be identifiable. This research is supported by Anglia Ruskin University research funds.

If you have any questions regarding any aspects of this study, please e-mail Sarah Lalor at XXX or Dr Sarah Waugh at XXX. Alternatively, phone Sarah Lalor on XXX or Dr Sarah Waugh on XXX

PARTICIPANT CONSENT FORM

What is the most effective visual acuity chart for children?

Name of child:

Main investigator and contact details: Sarah Lalor

Members of the research team: Dr Sarah J Waugh, Dr Monika Formankiewicz, Dr John Siderov

1. I agree for my child/children to take part in the above research. I have read the Parents Information Sheet and Participant Information Sheet which are attached to this form. I understand what my role will be in this research, and all my questions have been answered to my satisfaction.
2. I understand that I am free to withdraw from the research at any time, for any reason and without prejudice.
3. I have been informed that the confidentiality of the information I provide will be safeguarded.
4. I am free to ask any questions at any time before and during the study.
5. I have been provided with a copy of this form, the Parents Information Sheet and the Participant Information Sheet.

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

Name of parent or guardian (print)……………………….. …………………………...

Signed……………….………………………………………………… Date………………

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

PLEASE SIGN AND RETURN ONE COPY AND KEEP THE OTHER

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

Title of Project: What is the most effective visual acuity chart for children?

I WISH TO WITHDRAW FROM THIS STUDY

Signed: ___________________________________ Date: ______________________

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