ANGLIA RUSKIN UNIVERSITY

FURTHER INSIGHTS INTO LETTER CROWDING: THE ROLE OF CONTOUR INTERACTION, CONTRAST AND GAZE FIXATIONS

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B.Optom

A Thesis in partial fulfilment of the requirements of Anglia Ruskin University for the degree of Doctor of Philosophy

Submitted: February 2012

Dedication

To my parents

ACKNOWLEDGEMENTS

I would like to acknowledge my supervisors Drs John Siderov, Ebi Osuobeni and Sarah Waugh for their patience, help and support to the completion of this thesis. It is them who have taught me in valuing what research is all about. I would also like to thank Dr Monika Formankiewicz for her contribution towards programming.

Likewise, I am also glad to be with other past and present students from the lab Izzu, Veena, Norsham, Sarah, Akash and Karmelo. I would also like to thank Baskar, David, Susan, Raju, Carmen, Holly and Stephanie for their friendly support during the initial days of my PhD.

I would like to thank all my research participants RS, IH, SC, DD, PP, VG, KB, UD, JS, EO, PL, AB, RC, VS and SR. I respect and appreciate their help and this research couldn’t be done without the contribution of their valuable time. A special thanks to my dearest friends Bhuvan, Rajeev, Sam, Patrick and Anjani for their guidance, emotional support and financial help during the course of my study.

Most especially, I deeply thank my mom and brother for always standing by me during my highs and especially my lows, bearing with my impatience, tolerating my short temper and accepting me the way I am. I am blessed to have you specially people in my life

ANGLIA RUSKIN UNIVERSITY

ABSTRACT

FACULTY OF SCIENCE AND TECHNOLOGY

DOCTOR OF PHILOSOPHY

FURTHER INSIGHTS INTO LETTER CROWDING: THE ROLE OF CONTOUR INTERACTION, CONTRAST AND GAZE FIXATIONS

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FEBRUARY 2012

Visual acuity is reduced when optotypes are viewed in the presence of surrounding contours. This reduction in acuity is known as the crowding effect and is thought to be caused by a varying combination of contour interaction, gaze instability and attention. Traditional studies have used single optotypes surrounded by flanking bars to investigate crowding. Such targets may not realistically replicate the crowding effect inherent in clinical vision charts. The aim of this thesis was to systematically investigate the effect of crowding on visual thresholds in subjects with normal vision and in subjects with amblyopia, using specially designed charts.

In the 1st and 2nd experiment, contour interaction was assessed using a high (80 %) and low contrast (5.8%) Sheridan Gardiner repeat letter (SGRL) chart in subjects with normal vision. The effect of contour interaction was investigated by varying the inter-letter separation in the SGRL chart. Significant contour interaction was obtained at the abutting condition for both the contrast conditions. In the 3rd experiment the same protocol was repeated but in amblyopes. Significant contour interaction was obtained at

0.2 letter separation and the abutting condition for both the contrast conditions. The effect of contour interaction appears to be less for low contrast than for high contrast letters in normal, non-amblyopic and amblyopic eyes. Finally, in the 4^{th} experiment a Sheridan Gardiner Complex Interaction (SGCI) chart that requires imposed gaze fixations was constructed to measure visual acuity in normal's and amblyopes. The effect of any gaze instability on crowding was investigated by comparing SGRL thresholds to SGCI thresholds. The SGCI thresholds were higher than the SGRL thresholds at all the separations measured, suggesting an important effect of gaze instability on crowding.

In conclusion, this research has shown that gaze instability is an important component of the crowding effect for letter chart acuity measurements. Visual acuity especially when screening for amblyopia should be measured using a whole optotype chart that requires optotype to optotype fixation.

Key words: visual crowding, amblyopia, repeat letter chart, complex interaction chart, contour interaction, contrast and gaze fixations

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Chapter 1

General Introduction

Vision

Vision is one of the most important senses and has a profound effect on the quality of life (Kniestedt and Stamper, 2003). The visual process includes spatial (e.g. visual acuity, contrast sensitivity), colour and motion perception (Bailey, 1998; Elliott and Benjamin, 1998). However, in any eye examination the fundamental and basic requirement is accurate and repeatable measurement of visual acuity (Bailey, 1998).

Visual acuity is defined as the eye's ability to discriminate detail in an object (Bailey, 1998). Visual acuity measures are used to assess the status of the refractive errors, to determine the clinical outcome of eye diseases (Parr, 1981; Bailey, Bullimore, Raasch and Taylor, 1991) and in conditions such as amblyopia to assess visual performance at regular intervals of treatment (Hilton and Stanley, 1972; Simmers and Gray, 1999; Simmers, Gray, McGraw and Winn, 1999b). Visual acuity is affected by various factors which include refractive error, pupil size and retinal eccentricity (Kniestedt and Stamper, 2003; Herse and Bedell, 1989). Visual acuity scores are also limited by optical and neural factors (Campbell and Green, 1965; Bennett and Rabbetts, 1989). Further, the design of the chart is known to have a notable effect (Bailey, 1998; Bailey and Lovie, 1976; Raasch, Bailey and Bullimore, 1998; Hazel and Elliott, 2002; Hussain, Saleh, Sivaprasad and Hammond, 2006; Norgett and Siderov, 2011; Langaas, 2011). The legibility of the letters (Sloan, 1959; Bennett, 1965 cited in Sheridan and Gardiner, 1970; Bailey and Lovie, 1976; Hedin and Olsson, 1984; McMonnies, 1999;

McMonnies and Ho, 2000) is significant to determining visual acuity, in addition to the progression of letter sizes between rows (Bailey and Lovie, 1976; McGraw and Winn, 1993), the spacing between the adjacent letters (Liu and Arditi, 2000; Shah, Laidlaw, Brown and Robson, 2010; Norgett and Siderov, 2011) and the accuracy of fixational and saccadic eye movements (Flom, 1991).

Optotype identification is more difficult when surrounded or crowded by other features or targets (Ffooks, 1965; Keith, Diamond and Stansfield, 1972; Hilton and Stanley, 1972; Youngson, 1975; Friendly, 1978). Visual crowding is the phenomenon whereby visual acuity is adversely affected when optotypes are presented together instead of in isolation (Stuart and Burian, 1962). Flom (1991) suggested that crowding was due to the effect of contour interaction (the detrimental effect of visual acuity due to the influence of neighbouring optotypes), eye movements (fixational eye movements needed to fixate on each optotype that needs to be identified and saccadic eye movements needed to fixate from one optotype to another) as well as an attentional component (attention needed to separate a target optotype from the flanking optotypes while identifying each optotype in a linear or whole optotype chart).

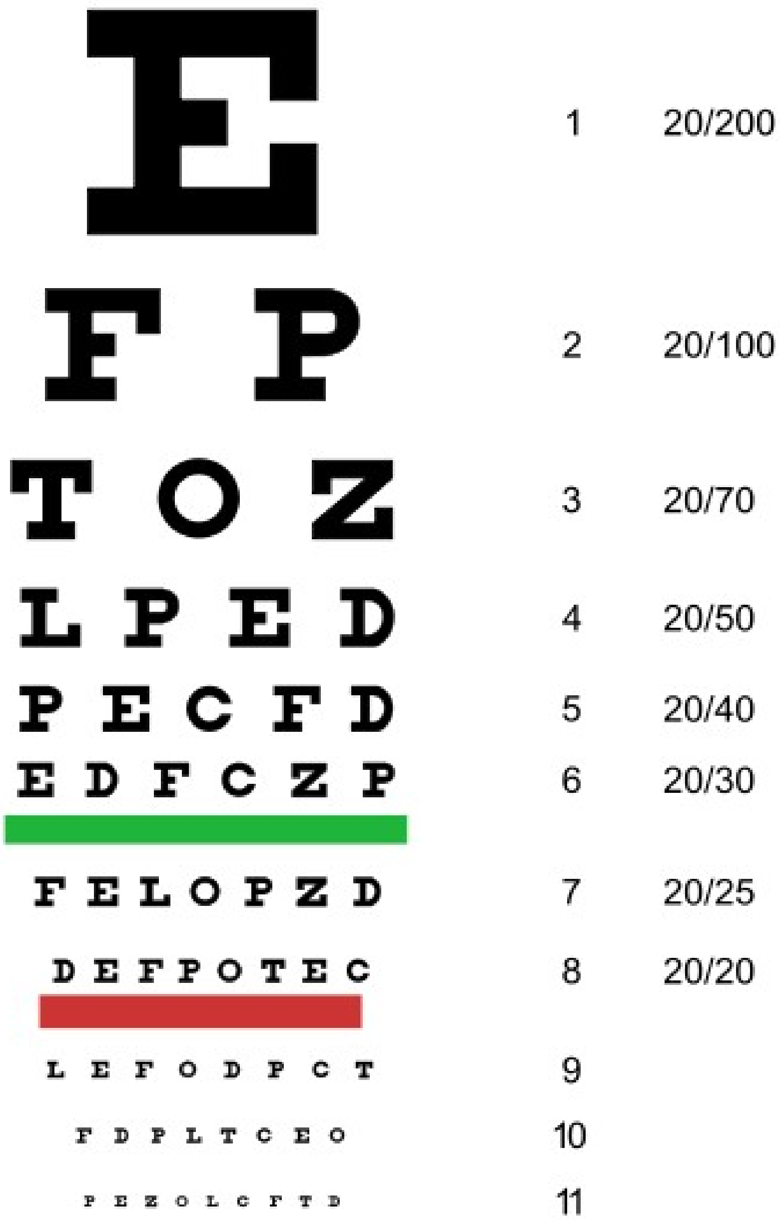
Although crowding is observed with other visual tasks such as stereopsis (Butler and Westheimer, 1978), vernier acuity (Levi, Klein and Aitsebaomo, 1985) and moving targets (Bex, Dakin and Simmers, 2003), this thesis is limited to the study of the effect of crowding on visual acuity measurement and its clinical implications.

Visual acuity charts

Snellen chart

The Snellen chart (Figure 1.1) was designed by Dr Herman Snellen in 1862. It consists of a series of serif letters with a single largest letter at the top and smaller size letters towards the bottom of the chart. Visual acuity is determined by the smallest line that a patient can read. The visual acuity score is designated as a fraction, where the numerator indicates test distance (6m or 20 feet) and the denominator denotes the distance at which the letter subtends 5 min of arc. In spite of its common use, the chart design has some limitations (Bailey and Lovie, 1976; Wick and Schor, 1984; McGraw, Winn and Whitaker, 1995; McGraw and Winn, 1993) with regards to clinical and research usage (Ferris, Kassoff, Bresnick and Bailey, 1982; Lovie-Kitchin, 1988). The letters are not equally legible (Bennett, 1965 cited in Sheridan and Gardiner, 1970; Kniestedt and Stamper, 2003). The acuity may therefore not be limited by the keenness of vision but by the difficulty of identifying a particular letter. The progression of letter sizes as well as the separation between the adjacent letters and rows lacks uniformity leading to variability in contour interaction and crowding (Bailey and Lovie, 1976; McGraw, Winn and Whitaker, 1995; Kniestedt and Stamper, 2003). These limitations can individually and/or collectively affect visual acuity scores and repeatability of visual acuity measurements (McGraw, Winn and Whitaker, 1995; Hussain, Saleh, Sivaprasad and Hammond, 2006; Lovie-Kitchin, 1988; Gibson and Sanderson, 1980).

Figure 1.1: The picture of a standard Snellen chart. This picture is adapted from http://en.wikipedia.org/wiki/File:Snellen_chart.svg



Bailey-Lovie LogMAR chart

The LogMAR chart was designed by Bailey and Lovie in 1976 (Bailey and Lovie, 1976). The rationale for this design, as seen in Figure 1.2, was the improvement in the shortcomings in the Snellen chart. The chart consists of a series of equally legible 10 non serifs letters (British Standards Institution, 1968) featuring 5 letters per row. The number of letters in each row is consistent throughout the chart. The space between these adjacent letters in each row is uniform and is equal to the width of the letter in that particular row. The space between rows is equal to the height of the letter in the subsequent lower line. The letters at the periphery of each row are not surrounded by other letters and would therefore be easier to identify as they are less crowded. The letter size changes in a geometric progression and each row varies by 0.1 Log units with each letter scored as 0.02 Log units. The specification of visual acuity in LogMAR units is considered the preferred standard visual acuity measurement scale (Bailey and Lovie, 1976; Westheimer, 1979; Bailey, Bullimore, Raasch and Taylor, 1991; McGraw, Winn, Gray and Elliott, 2000). Letter size is the only consideration that determines the visual acuity score due to the uniform chart design. Such a uniform chart design is believed to result in consistent and repeatable visual acuity scores (Lovie-Kitchin, 1988; Ferris, Kassoff, Bresnick and Bailey, 1982). As a result of this improvement in the chart design, legibility, contour interaction (except for the outer letters in the chart) and conceivably eye movements are all uniform in the LogMAR chart. Consequently, these improvements in the LogMAR chart have been accepted as a more accurate way to measure visual acuity for clinical and research purposes (Ferris, Kassoff, Bresnick and Bailey, 1982; Lovie-Kitchin, 1988; McGraw, Winn and Whitaker, 1995; Hussain, Saleh, Sivaprasad and Hammond, 2006).

Figure 1.2: The picture of a Bailey-Lovie LogMAR chart. This picture is adapted from http://www.sussexvision.co.uk/images/sdt2145.jpg

An accurate and repeatable measurement of visual acuity in children is important to detect early developmental anomalies such as amblyopia (Hilton and Stanley, 1972; Youngson, 1975; Simmers, Gray and Spowart, 1997; McGraw, Winn, Gray and Elliott, 2000). Amblyopia is generally characterised by decreased vision in one or both eyes commonly associated with anisometropia or strabismus (Noorden, 1974; 1985). Amblyopia is associated with perceptual deficits including reduced visual acuity (Noorden, 1985; Ciuffreda, Levi and Selenow, 1991; Simons, 2005) and reduced spatial contrast sensitivity (Levi and Harwerth, 1977; Hess and Howell, 1977; Bradley and Freeman, 1981). In this context, visual acuity assessment in amblyopic children proves challenging because of the poor visual function in amblyopic eyes (Sheridan and Gardiner, 1970; Keith, Diamond and Stansfield, 1972; Hilton and Stanley, 1972; Youngson, 1975; Simmers, Gray and Spowart, 1997; McGraw, Winn, Gray and Elliott, 2000). Various vision charts have been designed to measure visual acuity in children. Some of the commonly used vision charts for children are the Sheridan Gardiner (SG) isolated letter chart (Sheridan and Gardiner, 1970), Lea symbol charts (Hyvarinen, Nasanen and Laurinen, 1980), Kay pictures (Kay, 1983), Cambridge crowding cards (Atkinson, et al., 1985), Glasgow acuity cards (McGraw and Winn, 1993) and the H O T V test chart (Hered, Murphy and Clancy, 1997) (see Appendix 1).

Sheridan Gardiner (SG) isolated letter chart

Sheridan and Gardiner (1970) designed a new vision chart for children. The chart is based on a later version of the Stycar letter chart (Sheridan, 1960). The chart comprises of 7 non serif Snellen letters based on the psychological ability of a child to identify targets as a function of their age.

The 7 Sheridan Gardiner (SG) letters, A, H, O, T, U, X and V are presented in isolation. The chart is made easier to use in young children when provided with a matching key card. The isolated SG letter card is presented at 3m or 6m and the patient has to verbally respond or point out the matching letter on the key card. Although the chart is commonly used to measure visual acuity in children, it has some limitations (Sheridan and Gardiner, 1970; McGraw and Winn, 1993; Simmers, Gray and Spowart, 1997). Firstly, the SG letters are not equally legible (Bennett, 1965 cited in Sheridan and Gardiner, 1970; McGraw and Winn, 1993). Secondly, the reliability of the isolated SG acuity may be compromised by the Snellen scoring system as discussed earlier in this Chapter (Bailey and Lovie, 1976; McGraw and Winn, 1993; Simmers, Gray and Spowart, 1997; McGraw, Winn, Gray and Elliott, 2000). Thirdly, the isolated SG letters are not surrounded by any flanking letters or bars thus eliminating any effects of contour interaction or imposed eye movements that are required in normal clinical visual acuity charts. The lack of a crowding effect could lead to overestimation of the isolated SG visual acuity scores and as a result could limit the detection of any developmental anomalies such as amblyopia (Hilton and Stanley, 1972; Youngson, 1975; Simmers, Gray and Spowart, 1997).

Evidence regarding the limitations of the SG isolated letter chart was provided by Simmers, Gray and Spowart (1997) who compared children’s (5 to 6 years) visual acuity scores obtained using a SG isolated letter chart and a Glasgow acuity chart (linear array of 4 letters surrounded by a flanking box). The SG isolated letter acuity was significantly better than the Glasgow acuity by 0.23 Log units. Better SG isolated letter acuity may be due to the lack of contour interaction, lack of imposed gaze fixations and lesser attention needed while determining SG isolated letter acuity. The elimination of one or more of these factors has been suggested to lead to a relative overestimation of visual acuity scores. The SG isolated letter chart detected only 55% of the amblyopic subjects while the Glasgow acuity chart helped to detect 100% of amblyopic subjects. The results support previous reports of the decreased sensitivity of the SG isolated letter in identifying amblyopic children (Hilton and Stanley, 1972; Youngson, 1975).

The limitations of using an isolated letter chart emphasise the importance of increasing the sensitivity of such charts (Hilton and Stanley, 1972; Youngson, 1975; Parr, 1981; Atkinson, et al., 1985; 1988; Simmers, Gray and Spowart, 1997; Schlenker, Christakis and Braga-Mele, 2010). The sensitivity of vision charts has been improved by incorporating contour interaction or crowding in their design (Parr, 1981; Atkinson, et al., 1985; 1988; Atkinson, 1991; McGraw and Winn, 1993; Salt, Wade, Proffitt, Heavens and Sonksen, 2007). Contour interaction has been incorporated either by using flanking bars (Flom, Weymouth and Kahneman, 1963; Parr, 1981; Fern, Manny, Davis and Gibson, 1986; Vision in preschoolers study group, 2003; Schlenker, Christakis and Braga-Mele, 2010) or flanking letters (Atkinson, et al., 1985, 1988) around a single optotype. The contour interaction effect is determined as the difference between the flanked to isolated visual acuity scores (Fern, Manny, Davis and Gibson, 1986; Atkinson, et al., 1985, 1988). A crowding effect is incorporated by using a linear or multiple arrays of optotypes. Patients are required to read one letter after the other. Consequently, such a design would involve the effect of contour interaction, gaze fixations and a greater attention component. The crowding effect is determined as the difference between the linear or whole optotype acuity to isolated visual acuity scores (Rodier, Mayer and Fulton, 1985; McGraw and Winn, 1993; McGraw, Winn, Gray and Elliott, 2000). Examples of children’s crowded charts include the Cambridge crowding chart, Glasgow acuity chart and some of the crowded linear charts.

Cambridge crowding cards

The Cambridge crowding cards designed by Atkinson, et al. (1985) consist of a central Stycar letter surrounded by 4 random Stycar letters at 0.5 letter width separation from the central letter. The flanking letters are incorporated to maintain contour interaction to the central letter. A separation of 0.5 letter width may have been chosen based on the results of previous studies (Flom, Weymouth and Kahneman, 1963). A separation greater than 0.5 optotype width was demonstrated to show reduced intensity of contour interaction (Flom, Weymouth and Kahneman, 1963). However, other studies have shown that the effect of contour interaction in younger children begins at a wider separation of nearly 0.3 to 0.6 optotype widths when compared to older children and adults (Kothe and Regan, 1990b; Semenov, Chernova and Bondarko, 2000; Bondarko and Semenov, 2005; Jeon, Hamid, Maurer and Lewis, 2010; Norgett and Siderov, 2011). Therefore, a choice of 0.5 inter optotype separation is ambiguous in regards to maintaining contour interaction effect.

The Cambridge crowding ratio was determined in younger children (3 to 4 years), older children (5 to 7 years) and adults (35 ± 5 years) with normal vision (Atkinson, et al., 1985; 1988). The Cambridge crowding ratio was measured as a ratio of Cambridge crowding acuity to isolated letter acuity. The Cambridge crowding ratio was significantly greater in younger children (1.8 to 2) than the older children (1.2) and adults (1.2) (Atkinson, et al., 1985; 1988). Greater crowding in younger children could possibly be due to poor cognitive factors and greater extent of contour interaction in younger children than older children and adults (Manny, Fern and Loshin, 1987; Bondarko and Semenov, 2005; Semenov, Chernova and Bondarko, 2000; Norgett and Siderov, 2011).

In another study, Atkinson (1991) measured visual acuity in children (3-4 years) and adults with normal vision using a Cambridge crowding card (flanking letters positioned at 0.5 letter width separations from the central letter) and a flanked letter (flanking box positioned at 0.5 and 0.25 letter width separation from the central letter). In adults, the visual acuity was poorest with flanked letters surrounded by a crowded box at 0.25 letter widths, followed by Cambridge crowding cards and lastly with letters surrounded by crowded box at 0.5 letter widths. However, normal children showed greater crowding with the Cambridge crowding card than with the flanked letter. This could be because, firstly the target letter could be confused with one of the flanking letters and such confusion is minimal with the flanking box. Secondly, though children were instructed to fixate on the central target letter, the surrounding letter could induce a gaze fixation away from the central letter and subjects could mistakenly fixate on the flanking letters than the central letter. Such a distraction would be more influenced with the flanking letters than with the flanking box or bars. Atkinson (1991) showed that the effect of contour interaction would vary depending on the flanker type and is different between children and adults. Although attempts have been made to induce contour interaction in the Cambridge crowding cards, it has some limitations. Similar to the isolated SG acuity, the reliability of the Cambridge crowding acuity may be compromised by the Snellen scoring system. Though there could be a possible effect of instability of fixation on the central letter due to the surrounded flanking letters, there are actually no induced gaze fixations similar to a linear or a whole optotype chart design. Considering the limitations of the Cambridge crowding cards, crowded linear charts with induced effect of contour interaction and gaze fixations have been developed.

Glasgow acuity chart

The Glasgow acuity chart designed by McGraw and Winn (1993) is made up of 6 Stycar letters (H, O, U, X, Y, V) arranged in a linear array of 4 letters at each acuity level. Each linear array is surrounded by a crowding box whose width is equal to one fifth of the letter size to maintain contour interaction to all the letters in the linear array. However, Atkinson (1991) showed that the effect of contour interaction on visual acuity scores is different between flanking bars and flanking letters. Therefore, the Glasgow chart acuity scores may be different from scores obtained with other charts where the letters are surrounded by other letters. The inter-letter separation and the separation between the linear array of letters and the flanking box were maintained at 0.5 letter width separation. Potentially the sensitivity of the Glasgow acuity chart has been increased by the influence of contour interaction and imposed eye movements to fixate and identify each letter in the linear array and increased attention needed to separate a target letter from the adjacent letters. On the other hand, features such as letter size progression, visual acuity range and a Log based scoring system has been carefully considered and incorporated to allow for accurate and reliable visual acuity measurements with the Glasgow acuity chart.

In order to study the reliability of the Glasgow acuity chart in determining visual acuity, McGraw, Winn, Gray and Elliott (2000) compared the Glasgow acuity (in LogMAR scoring) to isolated letter acuity (in Snellen and LogMAR scoring) in visually normal children (4 to 6 years). The Glasgow acuity was significantly poorer than the isolated letter acuity (Log units) by 0.1 Log units. This could be because of the influence of crowding in the Glasgow acuity chart. In addition, the Glasgow acuity chart identified 100% of the amblyopic children while Snellen and Log based isolated letter charts identified 42.3% and 57.7% of amblyopic children respectively. McGraw, Winn, Gray and Elliott (2000) finding appears to be similar to the results of Simmers, Gray and Spowart (1997) who noticed that the Glasgow acuity chart identified 100% of amblyopic children while the isolated SG letter chart identified 55% of amblyopic children. McGraw, Winn, Gray and Elliott (2000) concluded that the isolated letter chart overestimates visual acuity scores and the Glasgow acuity chart that includes features such as the logarithmic scaling scores, induced contour interaction, imposed gaze fixations and attention components is sensitive for the effective detection of amblyopia. Later, many crowded linear charts have been constructed following the design pattern of the Glasgow acuity chart.

Crowded linear charts

Examples of crowded linear charts include crowded Kay pictures (Jones, Westall, Averbeck and Abdolell, 2003), crowded Lea symbol (Vision in preschoolers study group, 2010), crowded H O T V (Vision in preschoolers study group, 2010) and Sonksen LogMAR charts (Salt, et al., 2007). The optotypes e.g. Kay pictures, Lea Symbols, H O T V and Sonksen letters were initially designed in an isolated format (see Kay, 1983; Sheridan, 1960;

Lippmann, 1969; 1971). The optotypes were later surrounded by flanking bars at 0.5 letter width separation to incorporate contour interaction (Holmes, et al., 2001; Vision in preschoolers (VIP) study group, 2003). The crowding element in the charts is added by arranging optotypes in the form of a linear array similar to the Glasgow acuity chart.

Subsequently, studies were conducted to compare the reliability of visual acuity scores obtained with different vision charts. Jones, Westall, Averbeck and Abdolell (2003) measured visual acuity in normal children (2.5 to 16 years old) using a crowded linear Kay picture chart (0.5 optotype separation) and Glasgow acuity chart (0.5 optotype separation). However, it has to be considered that Kay pictures are constructed on 10x10 grid size and letters are constructed on 5x5 grid size. An inter optotype separation of 0.5 optotype width in a crowded linear Kay picture chart would actually be equivalent to 1.0 letter width separation in a Glasgow acuity. Though crowded Kay acuity was better than the Glasgow acuity by 0.08 Log units it was said to be clinically insignificant. Similarly, Elliott and Firth (2007) found no significant difference (nearly 0.1 Log units) in amblyopic children's (mean age 10 years 8 months) visual acuity scores when performance was compared between a crowded linear Kay picture chart (0.5 inter optotype separation) and a Glasgow acuity chart (0.5 inter-letter separation). Both the studies concluded that Crowded Kay picture optotypes could be used as an alternative to Glasgow acuity chart to measure visual acuity in children. Later, the Vision in Preschoolers (VIP) study group (2010) found that in children (3 to 5 years) with vision problems, acuity scores obtained with a crowded linear Lea chart (1.0 optotype separation) were better by 0.15 Log units when compared to the crowded linear HOTV chart (1.0 optotype separation) but are not statistically significant.

A significant difference in visual acuity scores was noticed when performance was compared between the charts having different design pattern. For e.g. the Vision in Preschoolers (VIP) study group (2003) found a significantly better visual acuity in children (3 to 3.5 years) by 0.25 Log units with a flanked HOTV chart (each letter surrounded by 4 equally spaced flanking bars at 0.5 letter width separation) than with a Lea optotype chart that was similar in design to a Bailey-Lovie LogMAR chart having 1.0 inter optotype separation. Similarly, Flom, Weymouth and Kahneman (1963) found that normal and amblyopic adults showed increased resolution thresholds when a complex interaction S chart acuity (1.0 inter optotype separation and that involves gaze fixations, see Figure 1.7) was compared to a flanked Landolt C acuity with flanking bars positioned at nearly 0.75 optotype width separations. Though the influence of contour interaction was found to be less in the Lea LogMAR chart (1.0 optotype separation) and complex interaction S chart (1.0 optotype separation) when compared to the flanked HOTV (0.5 optotype separation) and flanked Landolt C (0.75 optotype separation) respectively, poor visual acuity with the Lea LogMAR chart and complex interaction S chart may be due to the effect of involved gaze fixations and attentional components with a whole optotype chart than a flanked optotype chart.

In another experiment, McGraw, Winn, Gray and Elliott (2000) compared visual acuity scores in adults with normal vision (mean age 21.5 years) obtained using a Glasgow acuity chart (0.5 inter optotype separation) and a Bailey-Lovie LogMAR chart (1.0 inter-letter separation). Though poor visual acuity was expected with the Glasgow chart due to the narrower inter-letter separation, no significant difference in visual acuity scores (0.07 Log units) was noticed between both charts. This may be because of the cancellation of the increased effect of contour interaction (0.5 letter width separation) and decreased effect of gaze fixations (because of a linear array design) in a Glasgow acuity chart when compared to the decreased effect of contour interaction (1.0 letter width separation) and increased effect of gaze fixations (because of the whole letter chart design) in the LogMAR chart. More recently Norgett and Siderov (2011) determined visual acuity in normal children (4 to 9 years) using crowded Kay pictures, Sonksen LogMAR charts, Glasgow acuity chart, isolated SG letter and isolated Kay picture charts. The results showed a significant effect of vision chart on acuity scores.

In summary, vision charts varied in the design pattern as exemplified by the isolated letter chart, linear letter chart or whole letter chart. The above mentioned studies also explained that the factors such as contour interaction and gaze fixations contribute to the similarity or discrepancies between the visual acuity scores depending on the design of the vision charts. Therefore, these factors have to be carefully considered while attempting to increase the sensitivity of vision charts to screen for amblyopia.

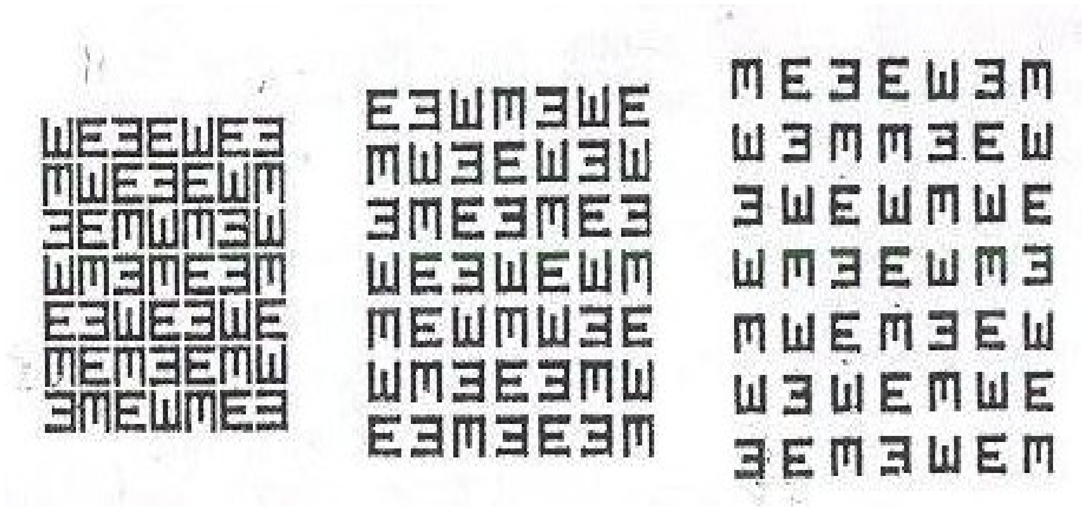
Contour interaction and gaze fixations in normal and amblyopic vision

The phenomenon of crowding has long been known (Ehlers, 1936 cited in Stuart and Burian, 1962), but the clinical importance of this phenomenon has gained increased attention following the experiments of Stuart and Burian (1962).

Stuart and Burian (1962) studied the phenomenon of separation difficulty in adults with normal and amblyopic vision. The separation difficulty was described as the differences between the smallest inter optotype separation where an optotype was just resolved, to the separation where nearly 82% correct responses were obtained. However, in their discussion they preferred to address the phenomenon as crowding rather than separation difficulty. Stuart and Burian (1962) performed an experiment where subjects were asked to resolve the direction of an optotype E presented in isolation and set in a 7x7 array (see Figure 1.3) with inter optotype separations varying from 1 to 45 mm (approximately 0.1 to 5.0 optotype separation for a 6/6 letter size).

Better resolution occurred with an isolated E than the array of E's. The subjects with 6/6 or better visual acuity had a separation difficulty of 5.6 mm. Alternatively, amblyopic subjects with 6/21 to 6/60 visual acuity had a separation difficulty of 39 mm. Stuart and Burian (1962) suggested that the extent of the separation difficulty or crowding was dependent on the measure of visual acuity scores in normal and amblyopic eyes. Although Stuart and Burian (1962) procedure required subjects to fixate from one optotype to another in an array of optotypes and the influence of unsteady gaze fixations on visual acuity was suggested especially in strabismic amblyopes, they had not enough evidence to support the role of gaze fixations towards visual crowding. Fixation instability would result in fixating on a flanking E rather than the target E or the one expected by the examiner thereby leading to poor visual acuity scores. Therefore, their explanation of crowding was based solely on the influence of the inter optotype separation on visual acuity scores. The effect of crowding on visual acuity was not disambiguated into the effect of contour interaction and unsteady gaze fixations.

Figure 1.3: Depicts the picture of E chart used in their study (Stuart and Burian, 1962, p.472).



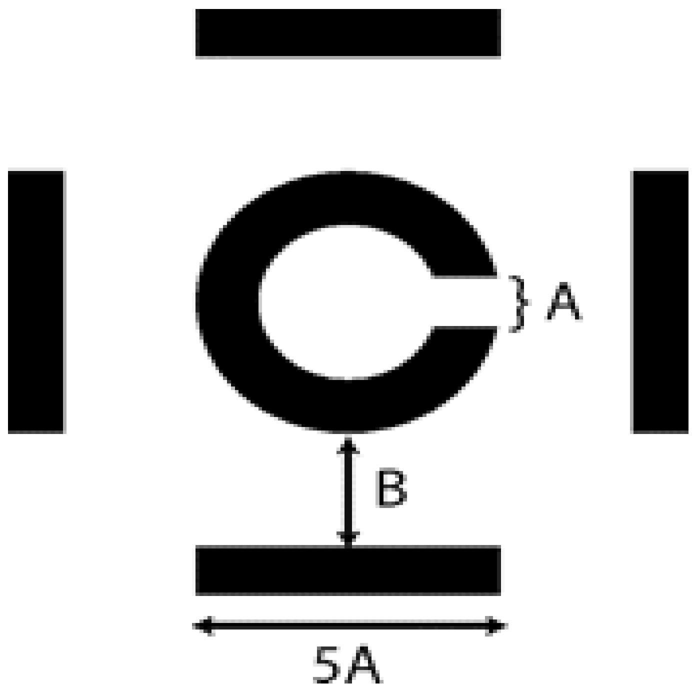
Maraini, Pasino and Peralta (1963) determined visual acuity using an isolated E and a linear array of six E's with 1.0 inter optotype separation. The separation difficulty was evaluated as the difference in visual acuity scores between the isolated and the linear array of E's. Maraini, Pasino and Peralta (1963) found that the separation difficulty was present (visual acuity better with the isolated E than the linear array of E's) in adults with normal and amblyopic vision. These findings were similar to the results of Stuart and Burian (1962), although Stuart and Burian (1962) measured separation difficulty with a 7 x 7 array of E's at a range of inter optotype separations, while Maraini, Pasino and Peralta (1963) measured separation difficulty with a linear array of 6 E's at 1.0 optotype width separation. It is therefore evident from Maraini, Pasino and Peralta (1963) results that both normal and amblyopic eyes experience separation difficulty/crowding with a linear array of optotypes separated by 1.0 optotype width. Additionally, Maraini, Pasino and Peralta (1963) observed greater separation difficulty in strabismic than in anisometropic amblyopes. The exaggerated separation difficulty in strabismic amblyopes may be due to greater fixation instability in strabismic than anisometropic amblyopes (Ciuffreda, Levi and Selenow, 1991). In a later study Flom, Weymouth and Kahneman (1963) showed that in adults with normal vision, the effect of contour interaction between

Landolt C surrounded by flanking bars was minimal at 1.0 optotype separation. Therefore, separation difficulty found at 1.0 optotype separation in normal subjects in Maraini, Pasino and Peralta (1963) study may be due to the involvement of gaze fixations while resolving the direction of each E in the linear array of E's. Both Stuart and Burian (1962) and Maraini, Pasino and Peralta (1963) studied crowding as a single entity and the effect of crowding on visual thresholds was not segregated into contour interaction effect and gaze instability. Further, both the studies used charts that are not controlled for contour interaction for the outer Illiterate E letters in the repeated chart and for Illiterate E letters that are arranged in a linear array. This may lead to non-uniform crowding between the outer and inner letters in the chart.

Later, Flom, Weymouth and Kahneman (1963) studied the extent and intensity of contour interaction in much detail. The aim was to quantify the contour interaction effect in adults with normal and amblyopic vision. Flom, Weymouth and Kahneman (1963) measured percentage correct performance of resolving the gap in a Landolt C as a function of the separation of four equally spaced flanking bars (see Figure 1.4). The separation between the C and the flanking bars varied from the abutting (Landolt C and flanking bars were touching each other) to 25 times the gap width (approximately 5 optotype widths separation). Flom, Weymouth and Kahneman (1963) noticed that for the normal and amblyopic eyes, the presence of the flanking bars had a minimal effect on the resolution of the gap in the Landolt C at large separations between the C and the flanking bars. In their subjects, the extent of contour interaction was at 2.8 min arc or 4.7 multiples of gap width (approximately 0.95 optotype width) in normal eyes and 12.5 min arc or 6.8 multiples of gap width (approximately 1.4

optotype width) in amblyopic eyes. Majority of their subjects showed an improved percentage of correct responses when the flanking bars were abutting the C. This improvement may be because of the provided spatial cue when the target forms a unitary picture (flanking bars touching the Landolt C) rather than when bars were separated at a critical distance from the Landolt C. On the other hand, some subjects showed maximum interaction at the abutting condition. Though the extent of contour interaction appeared larger in the amblyopic eyes (12.5 min arc) than the normal eyes (2.8 min arc) when the flanking bar separation was plotted in terms of minutes of arc, the extent of contour interaction was not very different between the amblyopic (6.8 multiples of gap width) and normal eyes (4.7 multiples of gap width) when the separation was plotted in multiples of gap width. Flom, Weymouth and Kahneman (1963) suggested that the extent of contour interaction when plotted in multiples of gap width scaled with the isolated visual acuity scores in the normal and amblyopic eyes.

Figure 1.4: Depicts the picture of Landolt C surrounded by four equally spaced flanking bars. The picture is adapted from http://www.iovs.org/content/51/11/6066/F1.expansion.html



Manny, Fern and Loshin (1987) carried out a similar study to Flom, Weymouth and Kahneman (1963) but in children (2 to 5 years old) with normal vision. They measured the percentage of correct responses as a function of separation using a square Landolt C with gap in the C presented only in the vertical direction and the gap is flanked by two equally spaced flanking bars ranging from abutting to 8.52 times the gap width (approximately 1.7 times optotype width separation). The maximal intensity of contour interaction was at 0.71 to 1.42 times the gap width (approximately 0.15 – 0.3 optotype width separation). Additionally, 4 out of 12 children (3 to 4 years) showed maximum intensity of contour interaction at the abutting condition similar to the findings of some subjects in Flom, Weymouth and Kahneman (1963) data. Manny, Fern and Loshin (1987) suggested that the intensity of contour interaction was nearly the same in children and adults, although the findings of other studies that showed greater extent of contour interaction in children than adults (Atkinson, et al., 1985; 1988; Kothe and Regan, 1990b; Semenov, Chernova and Bondarko, 2000; Bondarko and Semenov, 2005; Jeon, Hamid, Maurer and Lewis, 2010).

Jacobs (1979) measured visual acuity as a function of separation using a flanked Landolt C with flanking bars ranging from abutting to 5 bar widths (1.0 optotype width separation). Visual acuity was measured in adults with normal vision and at the fovea and periphery (up to 10 degrees). The extent of contour interaction was greater in peripheral retina (1.8 times the visual acuity with an isolated C) than at the fovea (1.4 times the visual acuity with an isolated C). In addition, all his normal subjects showed that the maximum intensity of contour interaction measured at fovea was at the abutting condition. This contradicts the findings of Flom, Weymouth and Kahneman (1963) and Manny, Fern and Loshin (1987) data who found that for most of their normal subjects, the maximum intensity of contour interaction ranged between 0.15 to 0.4 times optotype width separations but not at the abutting condition. Jacobs (1979) mentioned that the methodological differences where he measured visual acuity as a function of separation using flanked Landolt C while Flom, Weymouth and Kahneman (1963) measured percentage correct performance as a function of the separation may have contributed to the differences in the results between his and other studies (Flom, Weymouth and Kahneman, 1963; Manny, Fern and Loshin, 1987). Subsequently, Hess and Jacobs (1979) replicated Jacob (1979) experiment but in adults with amblyopic vision. Hess and Jacobs (1979) found that the contour interaction effect was greater in amblyopic eyes than normal eyes when measured at different retinal eccentricities. This was assumed to be due to poor peripheral retinal acuities in amblyopic eyes than normal eyes. Therefore, the notion of acuity scaling in normal and amblyopic fovea as proposed by Flom, Weymouth and Kahneman (1963) is not applicable to normal and amblyopic peripheral retina up to 10 degrees.

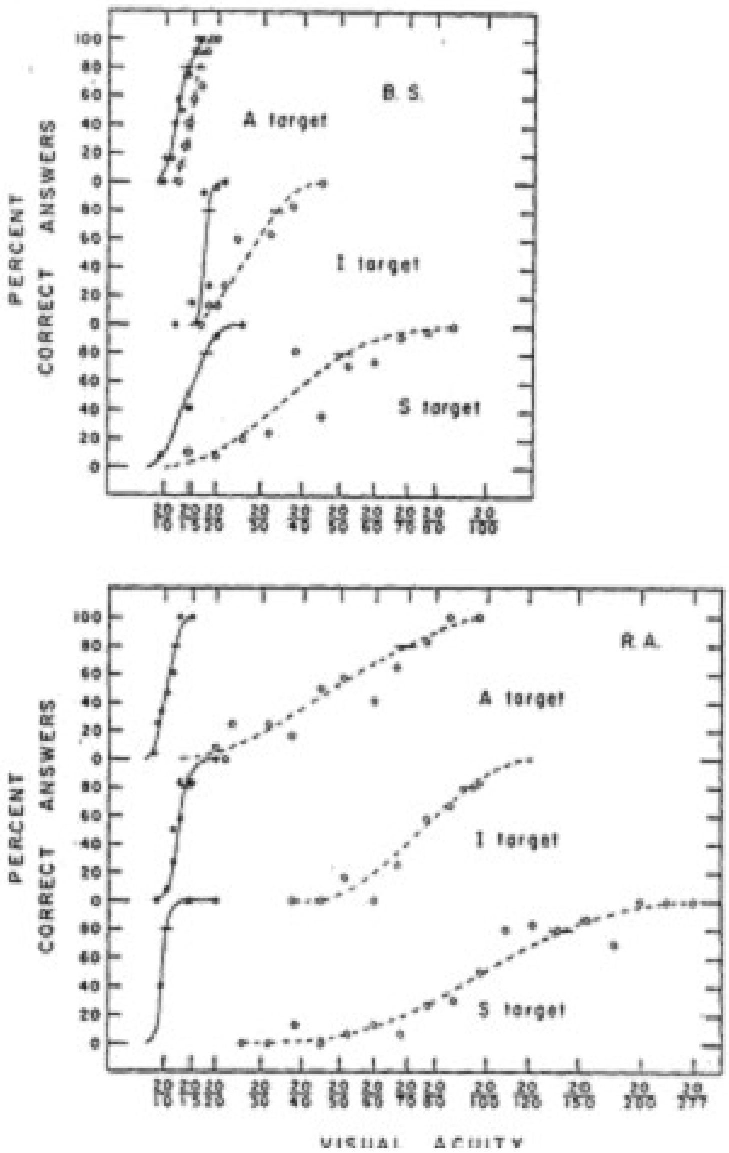
Additionally, Simmers, Gray, McGraw and Winn (1999a) measured the percentage correct responses in identifying Sloan letters as a function of the separation of four equally spaced flanking bars ranging from abutting to 1.0 letter width separation. The effect of contour interaction for high (80%) and low (6%) contrast Sloan letters was measured in adults with normal and amblyopic vision. Both the normal and the amblyopic eyes showed a maximum intensity of contour interaction at 0.4 letter width separation with the high contrast letters but no effect of contour interaction was seen with the low contrast letters. Contour interaction ratio (the ratio between the flanked conditions at 0.4 letter width separation to isolated letter) was greater for the high contrast letters by 25% to 30% than the low contrast letters. The results indicate that the contour interaction effect is dependent on the contrast levels of the visual stimuli because of the difference in performance under high and low contrast conditions. Simmers, Gray, McGraw and Winn (1999a) agreed with the findings of Flom, Weymouth and Kahneman (1963) - that contour interaction scales with visual acuity scores as both the normal and amblyopic eyes showed a contour interaction effect at 0.4 letter width separation.

Danilova and Bondarko (2007) determined the percentage of correct performance in resolving the gap in Landolt C as a function of separation of four equally spaced flanking bars, flanking Landolt C’s and flanking rectangular gratings of varying spatial frequencies. A second set of stimuli consisted of an illiterate E optotype presented in isolation and E surrounded by four equally spaced flanking E’s. A third set of stimuli consisted of a rectangular grating flanked by four equally spaced gratings of same or different spatial frequencies. Similar to Flom, Weymouth and Kahneman (1963) results - Danilova and Bondarko (2007) found that the maximal intensity of contour interaction between Landolt C and flanking bars was at 1-2 bar widths (0.2 to 0.4 optotype widths) separation. The percentage correct responses improved at the abutting condition between Landolt C and flanking bars. In contrast, the percentage correct responses maximally reduced at the abutting condition when the target and the flankers were the same (Landolt C surrounded by C's, illiterate E surrounded by E's and a grating surrounded by flanking gratings). Danilova and Bondarko (2007) suggested that the perception of the stimuli is influenced by the type of the flankers and their position on the receptive fields. In addition, resolving the gap in a Landolt C when surrounded by flanking bars though prone to gaze instability may not affect the visual acuity scores as fixating on flanking bars would not complicate in resolving the gap in the target Landolt C. Unlike the Landolt C flanked by 4 Landolt C's when influenced by gaze instability may affect the visual acuity scores, as subjects may fixate on the flanking Landolt C rather than the target Landolt C. This would result in more confusion from the flanking optotype that is the same as the target optotype, leading to maximum interaction at the abutting condition. Similarly, Leat, Li and Epp (1999) found that when a target C was surrounded by different distractors such as 4 flanking I's, 4 flanking square number 8, and 4 flanking C's, their adult subjects with normal vision showed maximum deterioration in visual acuity at the closest separation measured (in this case the separation between the target and the flankers was 1 min arc, This contradicts Flom, Weymouth and Kahneman (1963) results who found that most of their normal subjects showed maximum interaction at 0.2 optotype separation between Landolt C and flanking bars. In summary, the findings of these studies (Atkinson, 1991; Leat, Li and Epp, 1999; Danilova and Bondarko, 2007) suggest that the contour interaction effect may vary depending on the stimulus type- optotype surrounded by flanking optotypes or bars.

In a further experiment, Flom, Weymouth and Kahneman (1963) measured visual acuity using 3 different optotype configurations: an isolated Landolt

C, a flanked Landolt C with flanking bars at 3.75 multiples of gap width (approximately 0.75 letter widths) and what Flom, Weymouth and Kahneman (1963) called a complex interaction S chart. The complex interaction S chart consisted of an array of C’s arranged in an S shape pattern, with surrounding E’s more peripherally to provide constant level of contour interaction at the periphery of the chart (see Figure 1.7). The inter optotype separation in the complex interaction S chart was at 1.0 optotype width. Psychometric functions generated for each stimuli condition were compared between the non-amblyopic and amblyopic eye of two adult amblyopic subjects. The data from Flom, Weymouth and Kahneman (1963) are shown in Figure 1.5. The results of the isolated Landolt C thresholds (A target) were compared between the non-amblyopic (solid lines) and amblyopic eyes (dotted lines) (see Figure 1.5). The amblyopic eye of subject (BS) showed a minimal increase in the isolated C thresholds when compared to the fellow non-amblyopic eye, while the amblyopic eye of subject (RA) showed a significant increase in the isolated C thresholds when compared to the fellow non-amblyopic eye. The subject who had a minimal difference in the isolated C thresholds between the amblyopic and the non-amblyopic eye could escape the detection of amblyopia using a single optotype chart. This result shows that, in some amblyopic patients, single optotype charts may not be ideal to detect the presence of amblyopia. This is also evident from other studies (see Hilton and Stanley, 1972; Keith, Diamond and Stansfield, 1972; Fern, Manny, Davis and Gibson, 1986; Simmers, Gray and Spowart, 1997; McGraw, Winn, Gray and Elliott, 2000).

Figure 1.5: Depicts the data obtained from Figure 5 of (Flom, Weymouth and Kahneman, 1963, p.1029) paper.

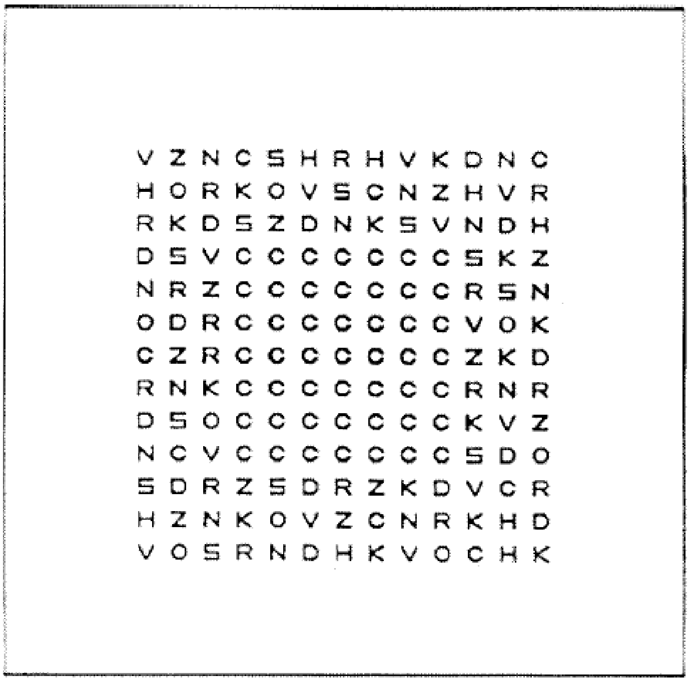


Further, both the amblyopic subjects showed increased resolution thresholds with the flanked C condition (I target) and complex interaction S chart (S target) when compared to the isolated C thresholds. The increase in the flanked and the complex interaction thresholds was minimal in the non-amblyopic eyes but was exaggerated in the amblyopic eyes. This could be because of the gradual decrease in resolution across a wider range of visual acuity scores in the amblyopic eyes thus leading to a flatter slope. Further, having a larger magnitude of gaze fixations in amblyopic eyes (0.5° to 8°) than normal eyes (5-10 min arc) (Schor, 1975) could lead to overshooting of saccadic fixation resulting in errors and could be the reason for exaggerated crowding in amblyopic eyes. Moreover, though the inter-optotype separation in the complex interaction chart (1.0 optotype width) was wider than the flanked Landolt C (nearly 0.7 optotype width), the increase in resolution thresholds was more for the complex interaction S chart than the flanked Landolt C in both the subjects. This increase in threshold was attributed to the additional requirement of gaze fixation from one optotype to another in the complex interaction S chart while the same is absent when using a flanked C. As Flom, Weymouth and Kahneman (1963) showed that when Landolt C is surrounded by flanking bars the extent of contour interaction was at 0.95 optotype width in normal eyes but at 1.4 optotype width in amblyopic eyes, the complex interaction S chart (1.0 optotype separation) controls for contour interaction in normal eyes but not in amblyopic eyes. Therefore, the complex interaction thresholds may be influenced by gaze fixations and contour interaction in amblyopic eyes but only by gaze fixations in normal eyes. Further, identifying each letter in a row involves imposed eye movements (saccade and fixation) and verbalizing the acquired and fixated optotype. Consequently, this is a complex task that requires greater attention than identification of an isolated optotype or an optotype surrounded by bars. Performance level on such a task is multifactorial (attention, eye movements and contour interaction) leading to a greater crowding effect. Though Stuart and Burian (1962) and Maraini, Pasino and Peralta (1963) used a slightly different paradigm to that of Flom, Weymouth and Kahneman (1963), the results of these studies show that crowding is present in normal eyes and exaggerated in amblyopic eyes. The findings of these studies reported crowding to be due to individual or a combined effect of contour interaction and gaze instability.

Alternatively, Kothe and Regan (1990b) aimed to investigate if crowding is chiefly due to the effect of contour interaction or gaze instability. Visual acuity was measured in children (4-11years) with normal vision using an isolated letter chart, a Snellen type chart and a Regan repeat letter chart (see Figure 1.6). The Regan repeat letter chart consists of an array of repeated Sloan letter in the centre, surrounded by randomised Sloan letters more peripherally to provide constant level of contour interaction to the outer repeated letters. The subjects had to identify the repeated Sloan letter irrespective of where they look in the central array of letters. The Regan repeat letter chart has a target letter surrounded by 8 flanking letters that are same as the target latter. On the other hand, a Snellen type chart used by Kothe and Regan (1990b) consisted of 11 Snellen rows with 8 letters per row. Each of the target letters in the Snellen type chart was not always surrounded by equal number of the flanking letters leading to sparse density of the flanking letters adjacent to a target letter in the Snellen type chart. Further, the adjacent letters are equally separated by 1 letter width in the vertical and the horizontal directions resulting in a uniform inter-letter spacing in the repeat letter chart. The inter-letter separation is 1 letter width in the horizontal direction but greater than 1 letter width in the vertical direction and the vertical separation changed between Snellen lines. Thus the density of the flanking letters surrounding a target letter is greater in the repeat letter chart than the Snellen type chart.

Kothe and Regan (1990b) hypothesised that the repeat letter chart is more sensitive to the effect of contour interaction because of the increased density of the letters in a repeat letter chart, but is less sensitive to gaze instability due to the repeated nature of the letters. On the other hand, the Snellen type chart is more sensitive to gaze instability due to the required gaze fixations to identify each letter on a Snellen line and increased possibility of making more errors due to different neighbouring letters. Kothe and Regan (1990b) showed that the mean isolated letter acuity was better than the mean repeat and mean Snellen acuity by nearly 0.06 and 0.30 Log units respectively. For some children the Snellen acuity was poorer than the repeat letter acuity. The poor Snellen acuity was interpreted to be due to the need to fixate on each letter in the Snellen line and any gaze instability may result in subjects substituting the target letter to a flanking letter. Some other children had poor repeat letter acuity than the Snellen acuity. The poorer repeat letter acuity was assumed to be due to the effect of contour interaction resulting from the increased density of the letters in the repeat letter chart than the Snellen chart.

Figure 1.6: Example of a Regan repeat letter chart (Kothe and Regan, 1990b, p.772)



Further, though the inter-letter separation in a repeat letter chart is maintained constant at 1.0 letter width where contour interaction is assumed to have a minimal effect on visual acuity scores in normal adults (see Flom, Weymouth and Kahneman, 1963), studies have shown that children could possibly have a greater extent of contour interaction than adults (Atkinson, 1991; Semenov, Chernova and Bondarko, 2000; Bondarko and Semenov, 2005; Jeon, Hamid, Maurer and Lewis, 2010). Therefore, poorer repeat letter acuity in some children could be due to the effect of contour interaction resulting from the 1.0 inter optotype separation in addition to the increased density of letters in the Regan repeat letter chart. Finally, some children had no significant difference between the repeat and the Snellen acuity and suggested that for these children there was a cancellation of the effect of contour interaction and gaze instability. In summary, Kothe and Regan (1990b) concluded that their repeat letter chart format could help to differentiate those children whose visual acuity is reduced due to gaze instability.

In subsequent work Regan, Giaschi, Kraft and Kothe (1992) replicated Kothe and Regan's (1990b) experiment. They compared the repeat letter acuity to Snellen acuity, but in children and adults with normal and amblyopic vision. The study was performed to discriminate between amblyopic visual acuity that was limited either due to contour interaction or gaze instability. They classified visual deficit as contour interaction (repeat letter acuity was poorer than Snellen acuity) and gaze instability (repeat letter acuity was better than the Snellen acuity). They found that some amblyopic children and adults had better isolated letter acuity than the corresponding repeat letter acuity and vice-versa. The results also showed that the poor visual acuity in amblyopic children was either due to the effect of contour interaction or gaze instability. However, poor visual acuity in amblyopic adults was due to the effect of gaze instability and not due to a contour interaction effect. This could be because of more fixational instability or immaturity in children (Aring, Gronlund, Hellstorm and Ygge, 2007). These results suggest that visual acuity is influenced by contour interaction at 1.0 optotype separation in children but not in adults as visual acuity in adults is not influenced by contour interaction when letters are separated by 1.0 letter width in a Regan repeat letter chart. This confirms the findings of other studies which showed a greater extent of contour interaction in children than adults (Atkinson, et al., 1985; 1988; Semenov, Chernova and Bondarko, 2000; Bondarko and Semenov, 2005; Jeon, Hamid, Maurer and Lewis, 2010). Also, each category of the visual deficit i.e.the repeat letter acuity being better than, equal to or poorer than the Snellen acuity included any kind of amblyopia (strabismic, anisometropic, strabismic+ anisometropic). Regan, Giaschi, Kraft and Kothe (1992) concluded that the comparison between the repeat letter acuity and Snellen acuity provides a non-invasive method of differentiating the amblyopic vision based on the type of the visual deficit and confirms the findings of Kothe and Regan (1990b) that a repeat letter chart differentiates subjects whose visual acuity is reduced due to gaze instability.

In another study, Simmers, Gray and Winn (1999) determined the effect of abnormal gaze fixations on visual acuity scores in subjects with congenital nystagmus and normal adults. Visual acuity was compared between the Regan repeat letter chart (1.0 letter width separation) and Glasgow acuity chart (0.5 letter width separation). Though the inter-letter separation seems different in both the charts, it is evident from the results of Flom, Weymouth and Kahneman (1963) that in normal adults, the intensity of contour interaction is minimal for separations greater than 0.4 letter widths. Therefore, the effect of contour interaction may possibly be controlled in both the charts at these optotype separations. Similar to the hypothesis of Kothe and Regan (1990b), Simmers, Gray and Winn (1999) stated that any significant difference between the repeat letter acuity and Glasgow acuity is attributed to the effect of gaze instability on visual thresholds. Simmers, Gray and Winn (1999) found that their normal subjects showed no significant difference (0.02 Log units) between the repeat letter acuity and Glasgow acuity. This implies that the effect of contour interaction and gaze instability did not limit visual acuity scores in their normal subjects. Contrary, subjects with congenital nystagmus showed significantly better repeat letter acuity by nearly 0.25 Log units than the Glasgow acuity. This implies that in these subjects, abnormal gaze fixations limit visual acuity using the Glasgow acuity chart. These results support the notion of Kothe and Regan (1990b) and Regan, Giaschi, Kraft and Kothe (1992) that the repeat letter acuity is less sensitive to the effect of gaze fixations or gaze instability.

Subsequently, research continued to monitor the efficiency of occlusion therapy in amblyopic adult (30 years old) (Simmers and Gray, 1999) and amblyopic children (mean age 5.6 ± 1.3 years) (Simmers, Gray, McGraw and Winn, 1999b). Visual acuity was measured using an isolated letter, high and low contrast Glasgow acuity chart and Regan repeat letter chart. The classification of visual deficit or improvement in visual acuity during the course of occlusion therapy was assessed in terms of contour interaction

(Glasgow acuity poorer than the isolated letter acuity), gaze instability (Glasgow acuity poorer than the repeat letter acuity), and abnormal contrast perception (low contrast Glasgow acuity poorer than the high contrast Glasgow acuity). The pre and post therapy findings of both the studies (Simmers, Gray, McGraw and Winn, 1999b; Simmers and Gray, 1999) showed a significant improvement in visual acuity by nearly 0.24 Log units during the course of occlusion therapy in both amblyopic children and adults. The improvement in visual acuity in amblyope adult showed that age is not a limiting factor for the treatment of amblyopia. Further, the nature of visual deficit in non-amblyopic and amblyopic eyes is pertinent to different components of visual functions such as abnormal contour interaction, fixation instability or deficit contrast perception. In brief, the findings suggested that it is extremely important to assess the different components of visual deficit such as contour interaction and gaze fixations while measuring visual acuity in normal and amblyopic subjects (Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992) and also while monitoring the course of the occlusion therapy (Simmers and Gray, 1999; Simmers, Gray, McGraw and Winn, 1999b).

Generally, a Regan repeat letter chart (see Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992; Simmers, Gray, McGraw and Winn, 1999b; Simmers and Gray, 1999; Simmers, Gray and Winn, 2000) and a multiple E chart (see Stuart and Burian, 1962) have been used to study the effect of visual crowding on visual acuity scores in normal and amblyopic subjects. Alternatively, repeated letter charts have been used in other studies to evaluate visual acuity scores in patients with macular hole and age related macular degeneration (Harris, et al., 1985; Horiguchi, Suzuki, Kojima and Shimada, 2001; Kadonosono, et al., 2003; Gonzalez, Tarita-Nistor, Markowitz and Steinbach, 2007; Cacho, Dickinson, Reeves and Harper, 2007). Kadonosono, et al. (2003) used a repeated E optotype chart to assess visual acuity scores in post-surgical macular hole patients, but not to study the effect of crowding. The inter optotype separation between E's was not mentioned and the effect of contour interaction was not determined. More recently, Gonzalez, Tarita-Nistor, Markowitz and Steinbach (2007) used a repeated E optotype chart but to measure visual acuity scores in patients with age related macular degeneration (ARMD). Visual acuity scores were compared between isolated E chart, repeated E chart at 2.0 optotype widths and an ETDRS chart with 1.0 optotype width separation. The subjects with ARMD had better repeated E acuity and isolated E acuity than visual acuity obtained with the ETDRS chart. Such a notion is consistent with Cacho, Dickinson, Reeves and Harper (2007) who measured visual acuity in patients with ARMD using an isolated Landolt C, crowded C (Landolt C surrounded by 4 flanking O's at 1.0 optotype separation) and repeated C chart with 1.0 optotype separation. The isolated C acuity and repeated C acuity were better than the crowded C acuity. This finding may be attributed to no effect of gaze instability on repeated visual acuity scores, in agreement to the findings of other studies (Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992; Simmers, Gray, McGraw and Winn, 1999b; Simmers and Gray, 1999; Simmers, Gray and Winn, 2000). In addition, Horiguchi, Suzuki, Kojima and Shimada (2001) assessed visual acuity in pre and post-surgical patients with a macular hole. Visual acuity was compared between repeated C charts with 0.2, 0.25 and 0.3 optotype width separation and a standard clinical Landolt C chart. A significant effect of separation on visual acuity was noticed at 0.25 and 0.2 optotype width separations while no significant effect was obtained at 0.3 optotype width separations. This finding is speculated to be due to increased effect of contour interaction at closer separations based on the findings of other studies (Liu and Arditi, 2000; Shah, Laidlaw, Brown and Robson, 2010).

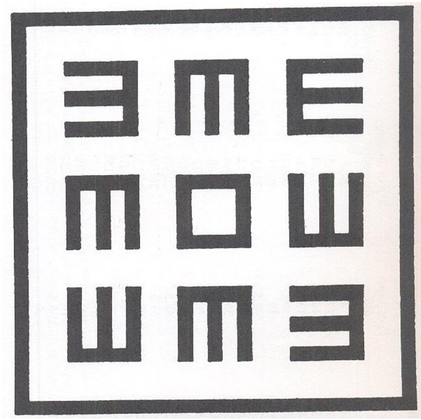
Though the studies discussed so far verified that the repeat letter acuity is less affected by gaze instability, generally eyes are never still and involuntarily make microsaccades, drifts and tremors (Ditchburn and Ginsborg, 1953). Previous studies have determined the magnitude of different kinds of eye movements such as saccadic (Robinson, 1964; Ciuffreda, Kenyon and Stark, 1978; 1979; Herishanu and Sharpe, 1981; Vlaskamp and Hooge, 2006), pursuit (Robinson, 1964; Schor, 1975) and drifts (Ciuffreda, Kenyon and Stark, 1980) in normal and amblyopic eyes. Previous studies have also shown that the magnitude of eye movements in amblyopic eyes could approximately vary between 0.5 to 8 degrees and reaching up to 28 degrees in some amblyopic eyes (Matteucci, 1960; Lawwill, 1968; Schor and Flom, 1975; Schor and Hallmark, 1978; Ciuffreda, Kenyon and Stark, 1980). Visual acuity measurement using a whole letter chart or linear acuity charts involves fixational eye movements in order to fixate on each letter in the chart and saccadic eye movements in order to move from one letter to other letter. Visual acuity in subjects with normal vision may probably not be affected by eye movements provided the saccadic eye movements are within the normal limits of 5 –10 min of arc (Ciuffreda, Levi and Selenow, 1991). However, the inability to maintain a steady fixation may result in errors where the intended direction of fixation is different to the expected direction of fixation (Flom, 1986). Such errors would result in variable or decreased visual acuity scores. This is more of a concern especially in amblyopic eyes because of poor fixation stability while fixating on a target (Schor and Flom, 1975; Schor, 1975; Schor and Hallmark, 1978; Srebro, 1983) or positional uncertainty where amblyopes are uncertain of the relative position of the target (Bedell and Flom, 1981; 1983; Levi, Klein and Yap, 1987; Bedell, Flom and Barbeito, 1985; Ciuffreda, Levi and Selenow, 1991; Hess and Holliday, 1992). The effect of crowding on visual acuity using a whole letter chart or a linear chart has been widely studied (Flom, Weymouth and Kahneman, 1963, Wick and Schor, 1984; McGraw and Winn, 1993; Liu and Arditi, 2000; Shah, Laidlaw, Brown and Robson, 2010).

Wick and Schor (1984) compared the complex interaction acuity to Snellen acuity in order to evaluate the validity of the charts to screen for amblyopia. The visual acuity scores obtained using both the charts were plotted in the form of psychometric functions. No significant difference in the Snellen and complex interaction acuity was noticed in subjects with acuity ranging from 6/9 to 6/24. This was speculated to be due to the minimal effect of contour interaction (nearly 1.0 and greater than 1.0 letter width separation) in both the charts at that acuity level. To the contrary, a significantly better Snellen acuity than the complex interaction acuity was noticed for the subjects with acuity ranging greater than 6/30. This was speculated to be due to a number of reasons that include fewer letters at larger letter sizes in a Snellen chart and a larger difference between the consecutive Snellen lines at larger letter sizes leading to lesser crowding of the Snellen chart. The Snellen acuity has no clear cut-off point to define threshold acuity. Further, the magnitude of eye movements may vary while using different charts though the letter sizes used in both the charts are the same. For e.g. a complex interaction S chart has an inter optotype separation of 1.0 letter width. Having a 10 min arc fixation instability can impair the aiming ability of a 6/6 letter at 6 m while using a complex interaction S chart and may result in the subject identifying a letter different to that instructed to identify. On the other hand a 10 min arc fixation instability may not impair the identification of a 6/6 letter at 6 m when a Snellen chart is used, because of the wider inter-letter separation of nearly 3.2 letter widths in a Snellen chart leading to no detrimental effect on visual acuity. This could be the reason why Wick and Schor (1984) found no significant difference between the complex interaction acuity and Snellen acuity only for the 6/9 Snellen line and above and not for the 6/6 Snellen line. The results also confirmed the importance of assessing amblyopic visual acuity with a chart that can produce a psychometric function and that contains uniform acuity levels, equal number of letters at each acuity level and uniform inter-letter spacing. Conclusively, the findings highlight the drawbacks of using a Snellen chart to measure visual acuity in agreement with the suggestions of other studies (see Bailey and Lovie, 1976; McGraw, Winn and Whitaker, 1995; McGraw and Winn, 1993).

A similar finding to Wick and Schor (1984) was reached by Davidson and Eskridge (1977), who compared the inter session variability of visual acuity obtained using a Snellen chart, a linear Snellen line and PVA test (psychophysical testing targets) (see Figure 1.7). The PVA chart is similar in design to a complex interaction S chart (see Flom, Weymouth and Kahneman, 1963) but with some modifications. The Landolt C's, the outer Illiterate E's and the inter-letter separation of one optotype width in a complex interaction S chart were replaced by Illiterate E's, a crowding box and an inter-letter separation of 0.5 optotype width respectively in a PVA test chart. Davidson and Eskridge (1977) found that the inter session variability for visual acuity thresholds was significantly different and less with the PVA test than the Snellen chart. This was believed to be due to the uniform crowding in the PVA chart compared to the Snellen chart. Davidson and Eskridge (1977) supported the findings of Wick and Schor (1984) and suggested that measuring visual acuity in the form of a psychometric function and monitoring the changes in the slopes of the psychometric curve during the course of an amblyopia therapy would be more beneficial than the conventional scoring system used in the Snellen type chart.

Figure 1.7: Example of a PVA test chart (Davidson and Eskridge, 1977, p.759) and Complex interaction S chart (Flom, Weymouth and Kahneman, 1963, p.1030).

PVA test chart



Complex interaction S chart

Liu and Arditi (2000) obtained the percentage of correct responses in identifying Sloan letters as a function of separation in adults with normal vision. The stimulus was a linear array of either four or five letters per array, with letter size ranging between 3.44 to 4.96 min arcs and with inter-letter separations ranging from 0.04, 0.08, 0.16 to 0.24 times the letter height. Liu and Arditi (2000) showed a decrease in the percentage of correct responses and increase in the underestimation of the number of letters in the linear array (the subjects gave 4 letter responses for an array with 5 letters) at the narrowest inter-letter separation (0.04 letter widths). For a linear array with a letter size of 3.44 min arc and having inter-letter separations ranging from 0.04, 0.08, 0.16 and 0.24 times the letter height, the visual angle between the two adjacent letters in the linear array may approximately subtend 3.48, 3.57, 3.74 and 4.08 min arc respectively. While the magnitude of eye movements range between 5 -10 min arc in normal eyes (Ciuffreda, Levi and Selenow, 1991), any fixation instability may result in overshooting of the saccadic fixations resulting in errors (intended direction of fixation is different to acquired direction of fixation) leading to decreased percentage of correct responses and underestimation of the number of letters in the linear array. Further an increase in the effect of contour interaction could also be the reason for the decreased percentage of correct responses at narrower inter-letter separation. Previous studies also showed that the letters in the periphery of the chart are easy to identify than the central letters in normal subjects (Estes and Wolford, 1971; Townsend, Taylor and Brown, 1971; Taylor and Brown, 1972; Bouma, 1973; Liu and Arditi, 2000; 2001) and amblyopes (Flom, 1986). This is believed to be due to lesser crowding and lack of contour interaction to the outer peripheral letters. Therefore, another possible reason for decreased percentage responses and underestimation of the number of letters may be due to more crowding for the inner letters resulting in missing or omission of the inner letters or merging of the neighbouring letters in the array.

Subsequently, Liu and Arditi (2001) obtained the percentage of correct responses while identifying 26 uppercase English letters of 3.44 to 4.23 min arc arranged in a linear array of 5 letters at wider (1.0 letter width) and narrower (0.1 letter width) separations. The errors obtained by comparing the stimulus and responses pairs were arranged in the form of a letter confusion matrix (LCM). The confusion patterns were described as common (significantly same confusions at wider and narrower letter separations), unique (significant confusions that occurred only at one of the letter separations and not the other) and random (insignificant confusions that occurred due to random guessing). Liu and Arditi (2001) found more random and unique confusions at narrower separation but less random and unique confusions at wider separation. Liu and Arditi (2001) speculated that the greater deterioration in visual acuity at narrower letter separation was due to random guessing resulting in more random confusions and unique confusions that are pertinent to narrower separations. However, based on the findings of previous studies (see Flom, Weymouth and Kahneman, 1963) the deterioration in visual acuity at narrower letter separation could also be due to the increased interaction between the adjacent letters in the array and the influence of gaze instability on letter recognition. Further, a shortcoming of the linear array of letters used in both the studies (see Liu and Arditi, 2000; 2001) is the lack of contour interaction to the linear array because of absence of a flanking box or flanking letters surrounding the linear array.

A recent study by Shah, Laidlaw, Brown and Robson (2010) has overcome this drawback by measuring visual acuity in adults with normal vision using a COMPlog chart. The COMPlog chart consisted of a linear array of 5 letters with inter-letter separations and a crowding box surrounding the linear array at 3.75 stroke width (0.75 letter width), 2.50 stroke width (0.5 letter width), 1.9 stroke width (nearly 0.4 letter width) and 1.25 stroke width (nearly 0.25 letter width) separation. Their purpose was to evaluate the accuracy and reliability of visual acuity measured using COMPlog charts with the gold standard ETDRS chart that has 1.0 letter width separation. No significant difference in the visual acuity scores (0.02 Log units) was noticed between both the charts (ETDRS and COMPlog) when COMPlog charts was presented at 0.75 and 0.5 letter widths separation. A significant effect of half LogMAR line was noticed between both the charts when COMPlog chart was presented at 0.4 and 0.25 letter widths. This could be because of the increased effect of contour interaction for separations less than 0.5 letter width separation (see Flom, Weymouth and Kahneman, 1963; Simmers, Gray, McGraw and Winn, 1999a). Shah, Laidlaw, Brown and Robson (2010) suggested that the inter-letter separations of 0.4 and 0.25 letter widths would be at the detrimental effect of crowding induced visual acuity loss. An inter-letter separation of 0.5 letter width may be ideal to be incorporated in vision charts. This suggestion is in agreement to some of the vision charts such as Cambridge crowding cards and Glasgow acuity chart that have a 0.5 inter optotype separation (see Atkinson, et al., 1985; 1988; McGraw and Winn, 1993). However, the experimental findings of Shah, Laidlaw, Brown and Robson (2010) were based on subjects with normal vision and it is unclear if the same separation would be ideal to measure amblyopic vision. This is because, having an inter-letter separation of 0.5 letter widths though controls for contour interaction may reduce the visual acuity caused due to gaze instability in amblyopes. A separation of 0.5 letter width in a vision chart may be at a detrimental effect of crowding induced vision acuity loss when measuring amblyopic vision.

To summarise, previous studies (Flom, Weymouth and Kahneman, 1963; Kothe and Regan, 1990b) suggested crowding to be due to the effects of contour interaction and gaze instability. A systematic consideration of the effect of contour interaction and gaze instability on visual acuity scores is important while designing a vision chart.

Crowding and contrast in normal and amblyopic vision

Visual acuity alone gives a poor prediction of real world vision as real world is not always composed of high contrast sharp edged objects (Owsley, 1994; Elliott, Bullimore, Patla and Whitaker, 1996). The visual system is best understood by obtaining both the high and low contrast information. Since the early 1960’s visual processing has been understood in terms of contrast sensitivity (Campbell and Green, 1965). The contrast sensitivity function predicts the status of visual problems more precisely which may not be detected with high contrast letters (Owsley and Sloane, 1987; Volkers, Hagemans, Wildt and Schmitz, 1987; Elliot and Benjamin, 1998; Brown and Lovie-Kitchin, 1989). The difficulty in measuring a contrast sensitivity function in routine clinical practice has lead to the development of low contrast vision charts (Regan and Neima, 1983; Regan, 1988; Pelli, Robson and Wilkins, 1988).The clinical application between the low contrast vision charts has been studied, and its importance in clinical practice in identifying visual problems has been emphasised (Regan and Neima, 1983; Woods and Wood, 1995).

Research has been carried out to determine the contrast sensitivity function in normal and amblyopes (Hess and Howell, 1977; Thomas, 1978; Bradley and Freeman, 1981). Amblyopes tend to show a loss of contrast sensitivity at different spatial frequencies depending on the intensity and the type of amblyopia. The anisometropic amblyopes are prone to an overall decrease in the contrast sensitivity function (CSF) while strabismic amblyopes are prone to decreased CSF at higher spatial frequencies (Hess and Howell, 1977; Thomas, 1978; Levi and Harwerth, 1978; Bradley and Freeman, 1981; Bedell and Flom, 1981; Sjostrand, 1981; Abrahamsson and Sjostrand, 1988). In addition to understanding the contrast sensitivity function in amblyopes, previous studies have investigated the influence of contrast on crowding in normal and amblyopic vision (Kothe and Regan, 1990a; Giaschi, Regan, Kraft and Kothe, 1993; Simmers, Gray, McGraw and Winn, 1999a).

Kothe and Regan (1990a) investigated the effect of contrast on crowding. Visual acuity was measured in normal children (5-12 years) using a Snellen type chart and isolated letter chart at high (96%), medium (11%) and low (4%) contrast levels. The crowding effect was defined as the difference between the Snellen to isolated letter acuity at each contrast level. The crowding effect was significantly greater for the high contrast letters by 30% to 40% than the low contrast letters. The greater crowding effect for the high contrast letters was assumed to be due to the influence of contour interaction, gaze instability and attention component on Snellen type acuity in agreement to the findings of other studies (see Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992). In contrast, Kothe and Regan (1990a) suggested that less crowding using the low contrast letters may be due to the weaker interaction between the adjacent low contrast Snellen letters, with resultant insensitivity to any gaze instability while fixating on each letter in the low contrast Snellen type chart. Additionally, previous studies showed poor visual acuity with the isolated low contrast than the isolated high contrast letters (Blommaert and Timmers, 1987; France and France, 1988; Sokol, Moskowitz, Reese and Brown, 1990; Strasburger, Harvey and Rentschler, 1991). This was assumed to be due to the requirement of detailed detection of letter features when identifying isolated low contrast letters. Therefore, reduced crowding in the low contrast stimulus condition may be due to lesser difference between the Snellen acuity and poor isolated acuity at low contrast level. Unlike greater crowding in high contrast stimulus condition may be due to greater difference between the Snellen acuity and better isolated letter acuity at high contrast level. Finally, Kothe and Regan (1990a) suggested that in normal children crowding depends on the contrast of the stimuli and is less for low contrast letters.

Subsequently, Giaschi, Regan, Kraft and Kothe (1993) replicated Kothe and Regan's (1990a) experiment, but the effect of contrast on crowding was measured in normal and amblyopic children (4-11years) and adults. Visual acuity was measured using a Snellen type chart and an isolated letter chart at the high (96%) and low (11%) contrast levels. A ratio of the Snellen to isolated visual acuity of greater than one indicated the presence of a crowding effect. Further, a ratio of high contrast to low contrast crowding effect of greater than one indicated greater crowding for the high contrast than the low contrast letters and vice-versa. They found that crowding was greater for the high contrast by 10% to11% than the low contrast letters in adults and children with normal vision in agreement to the findings of Kothe and Regan (1990a). On the other hand, the amblyopic eyes showed one of the three responses - greater crowding for the low contrast letters, lesser crowding for the low contrast letters or no difference between the high and the low contrast crowding effect. This might have clinical and functional importance because; amblyopic patients who showed reduced crowding for the low contrast letters may find it easier to read low contrast prints due to reduced crowding. Giaschi, Regan, Kraft and Kothe (1993) attributed that in their amblyopic subjects, the variable crowding effect may be due to the differences in the classification of visual deficit caused due to contour interaction and gaze fixations (see Regan, Giaschi, Kraft and Kothe, 1992). Regan, Giaschi, Kraft and Kothe (1992) noticed that some of his amblyopic subjects showed reduced visual acuity due to the influence of contour interaction while the reduced visual acuity in some other amblyopic subjects was due to the influence of gaze instability. Giaschi, Regan, Kraft and Kothe (1993) concluded that the crowding is contrast dependant and suggested that the amblyopic vision possibly be assessed with high and low contrast letters because of the difference in the crowding effect in the amblyopic eyes at both the contrast levels.

Alternatively, Simmers, Gray, McGraw and Winn (1999a) investigated the influence of contrast on contour interaction in adults with normal and amblyopic vision. The percentage correct responses in identifying Sloan letters was measured as a function of the separation using high (80%) and low contrast (6%) letters. The details of the study have been discussed earlier in this Chapter. The results showed that contour interaction was contrast dependent being greater for the high contrast and less or absent for the low contrast letters in normal and amblyopic eyes. Though the notion of reduced crowding or contour interaction for the low contrast condition is consistent in normal subjects in different studies (Kothe and Regan, 1990a; Giaschi, Regan, Kraft and Kothe, 1993; Simmers, Gray, McGraw and Winn, 1999a), the findings are contradictory in the amblyopic eyes. Simmers, Gray, McGraw and Winn (1999a) noticed that the contour interaction effect reduced for the low contrast in all of their amblyopic subjects. Unlike Giaschi, Regan, Kraft and Kothe (1993) who found that their amblyopic subjects showed either increased or reduced crowding for the low contrast stimuli condition. This difference in the results between Simmers, Gray, McGraw and Winn (1999a) and Giaschi, Regan, Kraft and Kothe (1993) amblyopic subjects may be due to the influence of imposed gaze fixations and variable contour interaction effect in a Snellen type chart leading to variable crowding, while the influence of any gaze instability on visual acuity scores is absent in Simmers, Gray, McGraw and Winn (1999a) target and visual acuity is affected only by contour interaction. Furthermore, the contrast sensitivity function is lower in amblyopic eyes than normal eyes and also depends on the type and degree of amblyopia (Levi and Harwerth, 1977; Hess and Howell, 1977; Thomas, 1978; Bradley and Freeman, 1981). Simmers, Gray, McGraw and Winn (1999a) and Giaschi, Regan, Kraft and Kothe (1993) used a fixed low contrast stimulus of 6% and 11% respectively. The results might be biased by the differences in the perceived contrast of the stimulus resulting from the differences in the contrast threshold deficit of amblyopic eyes.

Though somewhat less directly related in studying the effect of contrast on crowding, Strasburger, Harvey and Rentschler (1991) measured the contrast thresholds needed to identify a crowded number (middle number in the trigram) at the fovea and up to 4 degrees periphery. The size of the numbers ranged between 0.06° to 1.0° (0.72 to 12.0 optotype size) and the separation between the target and the flankers varied from 0° to 2.0° (abutting to 2 optotype separations). The results showed that the foveal contrast thresholds were independent of the separations and for all the optotype sizes measured. For e.g. for a trigram with 0.1° optotype size, a constant contrast of nearly 10% was needed to identify the middle number in the trigram when the flanking numbers were moved from further to closer the middle number. Similarly, for a trigram of with 0.2° target size, a constant contrast of nearly 4% was needed to identify the middle number in the trigram when the flanking numbers were moved from further to closer the target number. On the contrary, the contrast thresholds increased at peripheral retina when the target flanker separation was reduced. Though the implication regarding the effect of crowding on contrast is not direct, Strasburger, Harvey and Rentschler (1991) concluded that the foveal contrast threshold is unaffected at different separation conditions. Therefore, though Flom, Weymouth and Kahneman (1963) described crowding to be due to contour interaction and gaze fixations, an understanding of the effect of contrast on crowding is also important in normal and amblyopic vision.

Aim

The aim of this thesis is to systematically distinguish between the effects of contour interaction, contrast and gaze fixations on visual thresholds. This systematic segregation will help to separate the influence of each of the factors on visual acuity. This further helps to find out the factor that mostly contributes towards visual crowding in normal and amblyopic vision. This would add to knowledge to design a vision chart that would help to maximally increase the sensitivity of the chart but maintain the specificity for efficient screening of normal and amblyopic vision.

Rationale

To determine the effect of letter separation (contour interaction) on high contrast SG repeat letter visual acuity in normal and amblyopic vision

Visual crowding is described as a phenomenon where visual acuity is better with an isolated optotype chart than a whole optotype chart (Stuart and Burian, 1962). Clinical interest in the crowding effect stems from its relevance to the early detection of visual anomalies in children, notably amblyopia. Various studies have shown that an isolated optotype chart eliminates any influence of contour interaction or gaze fixations thereby overestimating the relative visual acuity scores (Keith, Diamond and Stansfield, 1972; Hilton and Stanley, 1972; Youngson, 1975). This led to the development of flanked and crowded linear charts (Flom, Weymouth and Kahneman, 1963; McGraw and Winn, 1993; Jones, Westall, Averbeck and Abdolell, 2003; Salt, et al., 2007; Vision in preschoolers study group, 2010) that incorporated contour interaction and gaze fixation elements. Previous studies have emphasised the influence of contour interaction (see Flom, Weymouth and Kahneman, 1963; Jacobs, 1979; Hess and Jacobs, 1979; Fern, Manny, Davis and Gibson, 1986; Manny, Fern and Loshin, 1987; Hess, Dakin, Kapoor and Tewfik, 2000; Simmers, Gray, McGraw and Winn, 1999a; Danilova and Bondarko, 2007) and gaze fixations (Flom, Weymouth and Kahneman, 1963; Flom, 1991; Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992; Simmers, Gray, McGraw and Winn, 1999b; Simmers and Gray, 1999) on visual thresholds.

Flom, Weymouth and Kahneman (1963) studied the effect of contour interaction using a Landolt C surrounded by four flanking bars at a range of different separations. The intensity of contour interaction was maximal at 1-2 bar widths (0.2 to 0.4 optotype separation) in normal eyes. The contour interaction effect scaled with visual acuity scores in normal and amblyopic eyes when separation was plotted in multiples of gap width. Later, many studies replicated the experiment of Flom, Weymouth and Kahneman (1963) and found that the influence of contour interaction ranged between abutting to 0.4 optotype width (Hess and Jacobs, 1979; Manny, Fern and Loshin, 1987; Danilova and Bondarko, 2007). Additionally, in another experiment, Flom, Weymouth and Kahneman (1963) compared visual acuity thresholds obtained using an isolated Landolt C, Landolt C surrounded by flanking bars at approximately 0.75 optotype width separation and a complex interaction S chart with 1.0 inter optotype separation. The non-amblyopic and amblyopic eyes showed increased resolution thresholds with the complex interaction S chart than the flanked Landolt C. Their results suggested that factors other than the proximity of flanking contours may be responsible for the increase in the crowding effect observed in a sequential letter acuity task, particularly for amblyopic subjects. Further, while attempting to make a saccadic eye movement from one optotype to another, over shooting and/or undershooting of optotype fixation could occur due to greater magnitude of eye movements in amblyopic eyes (0.1 -8.0 degree) than normal eyes (5-10 min arc) (Lawwill, 1968; Schor and Flom, 1975; Schor and Hallmark, 1978). The increase in threshold with complex interaction S chart was attributed to gaze instability resulting from the need to fixate and identify each optotype in the chart.

In most of the studies (Stuart and Burian, 1962; Maraini, Pasino and Peralta, 1963; Flom, Weymouth and Kahneman, 1963; Atkinson, et al., 1985; 1988; McGraw and Winn, 1993) the influence of crowding was explained as one entity and the effect of contour interaction and gaze fixations has not been quantified separately. Direct evidence of oculo-motor abnormalities in amblyopia has been available for some time (Schor and Levi, 1980; Schor, 1975) and the importance of the role of fixational eye movements in amblyopia has been reviewed (Martinez-Conde, Macknik and Hubel, 2004). Whilst direct measurements of normal fixational eye movements in conjunction with visual acuity measurements have not been reported, there is psychophysical evidence supporting a role of eye movements or relative gaze instability in visual acuity measurements. Attempts have been made to disambiguate the effect of contour interaction and gaze fixations on visual acuity scores. This was achieved by comparing repeat letter acuity that is less sensitive to any effect of gaze instability to Snellen acuity or Glasgow acuity that are more sensitive to gaze instability (Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992; Simmers, Gray, McGraw and Winn, 1999b; Simmers and Gray, 1999). The findings of these studies showed that in normal and amblyopic children and adults, the repeat letter acuity was better than the Snellen acuity and vice-versa (see Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992), and repeat letter acuity was better than the Glasgow acuity (see Simmers, Gray, McGraw and Winn, 1999b; Simmers and Gray, 1999). Poor Snellen and Glasgow acuity is attributed to be due to the additional requirements of gaze fixations to identify each optotype in the chart.

In summary, previous studies attempted to differentiate between the components of crowding (Kothe and Regan, 1990b). However, what is not known is, if the sensitivity of a vision chart to screen for amblyopia would be best increased by incorporating contour interaction or imposed gaze fixations. This is an important topic because, although numerous vision charts have been designed to measure visual acuity in children, the sensitivity of vision charts were believed to be increased by considering the contour interaction factor (Atkinson, et al., 1985; 1988; McGraw and Winn, 1993; Hazel and Elliott, 2002; Salt, et al., 2007; Schlenker, Christakis and Braga-Mele, 2010). Not much information is available regarding the impact of gaze fixations towards increasing the sensitivity of vision charts. Incorporating an appropriate crowding component in a vision chart is extremely important to increase the sensitivity, yet maintain the specificity of the chart, that possibly would help to detect amblyopia. Therefore, the gap in knowledge that needs clarification is, if crowding is influenced more due to the effect of contour interaction or due to imposed gaze fixations. In order to investigate this, crowding effect has to be systematically segregated into the effects of contour interaction and gaze fixations.

Firstly, previous studies that investigated contour interaction used a classic stimulus designed by Flom, Weymouth and Kahneman (1963) where a Landolt C was surrounded by flanking bars and it resembles a simple target. However, studies have shown that the effect of contour interaction could vary with flanker type (see Atkinson, 1991; Danilova and Bondarko, 2007). Further, whole letter charts such as the Snellen or LogMAR chart that are widely used to measure visual acuity in clinical practice consists of flanking letters and not flanking bars. It would therefore be preferable to study the contour interaction effect using flanking letters rather than flanking bars. Secondly, Flom, Weymouth and Kahneman (1963) described crowding as a combination of contour interaction, gaze fixations and attention. To solely study the effect of contour interaction on crowding, factors such as gaze fixations and attention have to be minimised. These above mentioned criteria necessitate the need to study the effect of contour interaction on visual thresholds using a whole letter chart design where contour interaction is induced using flanking letters and visual acuity obtained with such a chart is less sensitive to any effect of gaze fixations and attentional factors.

One such chart that satisfies the criteria of having multiple optotypes and that is less sensitive to the effects of erroneous gaze fixations is a Regan repeat letter chart designed by Kothe and Regan (1990b). The use of a repeat letter chart format may be a useful tool to investigate the crowding effect and in particular to determine the relative influence (if any) of oculomotor instability in sequential letter chart measurements. Though the Regan repeat letter chart has been used for research purposes (Reeves, Wood and Hill, 1993; Hazel and Elliott, 2002), using its modified version with SG letters to investigate contour interaction effect at different levels of inter-letter separation is novel. This chart consists of the same letter repeated in a 7x7 array. The subject’s task is to identify the repeated letter within the array. Consequently, the detrimental effect of inaccurate eye movement patterns on letter identification is minimised or even eliminated. Also, because the letters in the array are the same, any fixation inaccuracies will not lead to verbalization of a different letter. This arrangement also means that the task is less complex and requires less attention based on the fact that, at the fovea, minimal attention is required to identify a target optotype that is flanked by optotypes that are the same as the target optotype (see Leat, Li and Epp, 1999).

Further, a number of studies have shown that the error rate or the confusion between letters is influenced by the separation between the letters (Liu and Arditi, 2001). Liu and Arditi (2001) showed that there were more random errors at closer (0.1 letter width) than wider (1.0 letter width) separations. However, Liu and Arditi (2001) used a linear array of random Sloan letters where any gaze instability may replace a target letter to the flanking letter, leading to confusion of letters and thereby reduced visual acuity scores. On the other hand, other studies showed that the target flanker similarity can increase crowding (Kooi, Toet, Tripathy and Levi, 1994; Nazir, 1992). Although an explanation of this effect is not fully established, one possibility is that the similarity between the target and flankers creates an ambiguous percept based on the process of integration of relevant features of the target and flanker (Townsend, 1971; Loomis, 1990; Gervais, Harvey and Roberts, 1984). On the assumption that such a process plays a role in crowding, the use of repeat letter charts would present an interesting test of this model as the 'features' within the repeat letter chart are all the same.

Therefore, a study was conducted to investigate the effect of varying inter-optotype separation on visual acuity measured using a Sheridan Gardiner repeat letter (SGRL) chart format and in normal and amblyopic vision. The SGRL acuity thus obtained is sensitive to the effect of contour interaction and presumably less sensitive to the effects of gaze fixations and attention component. The effect of contour interaction is hypothesised to be more pronounced at closer separations between the target and the flankers because of the multiple and repeated arrangement of letters where the recognition of the letter shifts from a local to a global basis. It is further hypothesised that the effect of contour interaction would scale between non-amblyopic and amblyopic eyes as the SGRL acuity is influenced only by contour interaction effect and not gaze fixations and attention. Further, the effect of letter type on contour interaction was investigated using SGRL charts. This would help to evaluate the importance of considering equally legible letters in vision charts such as H O T V (Hered, Murphy and Clancy, 1997) and SG (Sheridan and Gardiner, 1970) test charts that are mostly used to measure visual acuity in children.

To determine the effect of letter separation (contour interaction) on low contrast SG repeat letter visual acuity in normal and amblyopic vision

Traditional clinical vision charts are made up of high contrast optotypes. However, objects in the visual field have varying contrasts from low to high. High contrast target visual threshold may not necessarily correlate with a patient’s perceptual response. For example, a patient with cataract may complain vigorously about poor vision even though the high contrast visual acuity may be quite good (Elliott, Bullimore, Patla and Whitaker, 1996; Owsley, 1994). Therefore, the effect of low contrast on contour interaction was investigated using the SGRL chart as a tool.

Kothe and Regan (1990a) investigated the effect of contrast (96%, 11%, and 4%) on crowding in normal children. The crowding effect for the low contrast letters was reduced by approximately 40% relative to the high contrast letters values. Kothe and Regan (1990a) in their discussion supposed that some amblyopic eyes have reduced crowding with low contrast letters like the normal eyes. They argued that this may lead to better reading with low contrast optotypes for such amblyopes. Consequently, it is important to study the effect of contrast on crowding or contour interaction in normal and amblyopic subjects.

Similarly, Giaschi, Regan, Kraft and Kothe (1993) compared the effect of contrast (96% and 11%) on crowding in normal and amblyopic children and adults. The normally sighted subjects showed a reduction in low contrast crowding of about 10% of the high contrast crowding value. The reduced crowding effect for the low contrast letters was assumed to be due to the weaker interaction between the adjacent low contrast letters. However, the nature of this “weaker interaction” was not explained. Further, the performance on a Snellen type chart (as used in Giaschi, Regan, Kraft and Kothe (1993) and Kothe and Regan (1990a) study) could be affected by attention (chart complexity), eye movement inaccuracies and contour interaction. Any of these three factors could be compromised by using low contrast, the effect of which is manifested as reduced crowding.

On the other hand, Giaschi, Regan, Kraft and Kothe (1993) found variable crowding effect in subjects with amblyopic vision. Based on the findings of Regan, Giaschi, Kraft and Kothe (1992), the difference in crowding effect in amblyopic eyes was attributed to the variable contribution of contour interaction and inaccurate gaze fixations to the phenomenon of crowding. According to this explanation, subjects in whom contour interaction plays a greater role in crowding will perform better on the Snellen chart than the repeat letter chart. Similarly, subjects with greater gaze instability contribution will have better repeat letter acuity than the Snellen acuity. Consequently the findings of previous studies (Kothe and Regan, 1990a; Giaschi, Regan, Kraft and Kothe, 1993) cannot be explained solely by contour interaction as the Snellen type chart included a combination of contour interaction, gaze fixation and attention components.

Alternatively, Simmers, Gray, McGraw and Winn (1999a) studied the effect of contour interaction on visual acuity using high and low contrast Sloan letters surrounded by flanking bars. Unlike Giaschi, Regan, Kraft and Kothe (1993) results, the contour interaction was not variable and was less for the low contrast letters in all the normal and amblyopic eyes. However, Giaschi, Regan, Kraft and Kothe (1993) and Simmers, Gray, McGraw and Winn (1999a) used a constant low contrast target and the results could be influenced by the variation in the contrast threshold deficit of the amblyopic eyes depending on the degree of amblyopia. Further, the target used in Simmers, Gray, McGraw and Winn (1999a) experiment is less sensitive to imposed gaze fixations and attention and highlights the contribution of low contrast on contour interaction. However, this type of target is different from what is obtained in a typical clinical vision chart where letters are surrounded by other letters.

Further, Alexander, Xie and Derlacki (1997) measured visual acuity and contrast sensitivity for individual Sloan letters. They found that the threshold log contrast for small sized letters (0.1 and 0.2 LogMAR) is different between the Sloan letters. Letter “O” was consistently hardest (required greater contrast at threshold) for all their subjects, while letters “H” and “V” were relatively easier. These three letters form a part of the SG letter set. The above finding demonstrated that different letters have different threshold log contrast for detection that could ultimately effect contour interaction. This may have important implications for optotype selection for the purpose of chart construction.

Consequently, it would be preferable to study the effect of low contrast on contour interaction by using a chart that is similar to a clinical visual acuity chart (letters surrounded by other letters) but at the same time that is less sensitive to the effect of imposed gaze fixations and attention. This could be achieved by using a low contrast SGRL chart.

In studying the effect of contrast on contour interaction it is imperative that targets should be presented at the effective low contrast level. Herse and Bedell (1989) showed that visual acuity remains constant when the contrast of the stimuli reduces from 100% to 20%. A poorer visual acuity was noticed when the contrast of the stimuli was less than 20%. Based on the reasoning above, it is important that low contrast letters need to be presented at values lower than 20% for any possible effect of contrast on contour interaction to be elicited. There is also evidence that for both amblyopic and non-amblyopic eyes the visual acuity for an isolated low contrast letter is poor than that of a similar sized high contrast isolated letter (France and France, 1988; Regan, 1988; Sokol, Moskowitz, Reese and Brown, 1990). Also, the contrast sensitivity function in amblyopic eyes is reduced and different from that of a normal eye (Hess and Howell, 1977; Levi and Harwerth, 1977). As a result of reduced spatial contrast sensitivity, the perceived contrast of a target with the amblyopic eye (AE) may be lower than in a non-amblyopic eye (NAE).

In this experiment, the effect of low contrast on contour interaction is investigated in normal and amblyopic vision using a SGRL chart consisting of the repeated SG letters at a range of letter separations. The effect of contour interaction is hypothesised to be less for the low contrast than the high contrast letters in normal and amblyopic vision as this study solely investigated the effect of contour interaction on contrast and the effect of gaze fixations and attention component on SGRL acuity is minimal.

To investigate the effect of letter separation and gaze fixations between SG repeat and SG complex visual acuity measurements in normal and amblyopic vision

Previous studies have investigated the effect of crowding on visual acuity scores as a single entity (Stuart and Burian, 1962; Maraini, Pasino and Peralta, 1963; Flom, Weymouth and Kahneman, 1963; Atkinson, et al., 1985; 1988; McGraw and Winn, 1993; McGraw, Winn, Gray and Elliott, 2000; Liu and Arditi, 2001). Other studies segregated crowding effect into contour interaction and gaze fixation elements by comparing Regan repeat letter acuity to Snellen acuity or Glasgow acuity (Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992; Simmers, Gray, McGraw and Winn, 1999b). Previous studies have investigated the effect of gaze fixations on visual thresholds at 1.0 optotype width separation using a complex interaction S chart (Flom, Weymouth and Kahneman, 1963), at 0.5 letter width separation using a Glasgow acuity chart (Simmers, Gray, McGraw and Winn, 1999b; Simmers, Gray and Winn, 2000) and at varying inter-letter separations in the vertical direction using a Snellen type chart (Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992). On the other hand, it is evident from Davidson and Eskridge (1977) and Wick and Schor (1984) that a complex interactions S chart or PVA tests chart than a Snellen type chart would be ideal to assess visual acuity especially in amblyopes. The variable crowding effect results obtained in different studies led to the indistinct information regarding the effect of contour interaction and gaze fixations on visual crowding (Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992; Giaschi, Regan, Kraft and Kothe, 1993).

Further, studies showed that amblyopes are prone to defective selection where the subjects can presumably identify a correct letter in the vision chart but report a wrong letter (Regan, Giaschi, Kraft and Kothe, 1992). Also, studies showed that amblyopic eyes are more prone to positional uncertainty and spatial distortion than normal eyes (Bedell, Flom and Barbeito, 1985; Barbeito, Bedell and Flom, 1988; Ciuffreda, Levi and Selenow, 1991). A gaze instability of 5 min arc may result in over shooting of saccadic fixation and may result in reporting a wrong letter on a 6/6 Snellen line at 6m and having 1.0 inter-letter separation. The overshooting of letters may be exaggerated in amblyopes due to greater magnitude of eye movements of about 0.1 to 8 degrees (Ciuffreda, Levi and Selenow, 1991). While objectively measuring a 5 min arc error can be demanding, it is hard to determine the reduced visual acuity that is caused due to gaze instability. Though Flom, Weymouth and Kahneman (1963) hypothesised gaze fixations as a possible factor towards visual crowding, especially in amblyopes, no psychophysical or oculomotor evidence occurs to demonstrate the reduction in visual acuity caused due to the extent of gaze instability as a function of letter separation. Consequently, the effect of contour interaction and gaze fixations on visual thresholds would possibly be understood better by psychophysically determining the effect of gaze fixations over contour interaction.

The final set of experiment will investigate the effect of gaze fixations on visual thresholds at a range of separations and in both normal and amblyopic vision. This was achieved by comparing the SGRL acuity to SG complex interaction (SGCI) acuity. The SGCI chart that is similar in design to a complex interaction S chart (Flom, Weymouth and Kahneman, 1963) presents the need for fixational eye movements to fixate on each letter and saccadic eye movements to identify each letter in the row. Any gaze instability could result in errors where the intended direction of fixation is different to the acquired fixation. However, no such errors would occur in a SGRL format as any fixational or saccadic inaccuracies would not result in eyes fixating a wrong or a different letter, provided the fixations remain within the 7x7 array of repeated letters. The SGRL acuity is less sensitive to gaze instability and SGCI acuity is susceptible to gaze instability. Therefore, the difference between the SGRL thresholds to SGCI thresholds presented at a range of constant inter-letter separations (the separations used are same in the SGCI chart and SGRL chart) would psychophysically determine any reduced visual acuity caused due to gaze instability at each of the separation condition that may not be achieved through oculomotor measurements. Further, to analyse the type of fixational instability on visual thresholds, substitution errors (caused due to fixating on flanking letters surrounding a target letter) and random errors (caused due to random guessing) are assessed at wider (1.0 and greater than 1.0 letter width) and narrower (0.2 letter width and abutting) separations. The details of the comparison between the SGRL and the SGCI thresholds, the influence of the substitution and random errors on SGCI thresholds at wider and narrower inter-letter separations are discussed in the final Chapter. Gaze instability is hypothesised to be a more contributory factor towards visual crowding if SGCI acuity is poorer than SGRL acuity at each of the constant inter-letter separations used in the experiment. Therefore, comparison between the SGCI thresholds to SGRL thresholds at constant separations would be a tool to investigate the most contributory factor towards visual crowding.

Summary

In the introduction Chapter, the demand for measuring visual acuity using a reliable chart and the importance of assessing different components of visual crowding has been discussed. This Chapter has highlighted the need for a standardised vision chart that is sensitive enough to elicit amblyopia easily. The subsequent experimental Chapters will explain the factors affecting crowding and their consequences on visual thresholds in detail.

Chapter two: To determine the effect of contour interaction on high contrast SG repeat letters in subjects with normal vision

Chapter three: To determine the effect of contour interaction on low contrast SG repeat letters in subjects with normal vision

Chapter four: To determine the effect of contour interaction on high and low contrast SG repeat letters in subjects with amblyopic vision

Chapter five: To investigate the effect of contour interaction and gaze fixations between SG repeat and SG complex visual acuity measurements in subjects with normal and amblyopic vision

Chapter six: Conclusions and future work

Chapter 2

The effect of contour interaction on high contrast SG repeat letters in subjects with normal vision

Introduction

Previous studies have shown that isolated letter charts overestimate relative visual acuity scores and may impair the detection of amblyopia (Stuart and Burian, 1962; Hilton and Stanley, 1972; Youngson, 1975; Simmers, Gray and Spowart, 1997; McGraw, Winn, Gray and Elliott, 2000). Studies have emphasised the importance of increasing the sensitivity of vision charts in order to detect amblyopia more easily (Fern, Manny, Davis and Gibson, 1986; Parr, 1981; Atkinson, et al., 1985; 1988; McGraw and Winn, 1993). The sensitivity of vision charts has been increased by introducing crowding components. Stuart and Burian (1962) were one of the first to demonstrate crowding in normal and amblyopic vision. Crowding was described to be due to contour interaction, gaze instability and attention (Flom, Weymouth and Kahneman, 1963; Flom, 1991). However, the stimuli used by Flom, Weymouth and Kahneman (1963) (Complex interaction S chart) and Stuart and Burian (1962) (7x7 array of E’s at a range of inter optotype separation) could not differentiate between the effects of contour interaction and gaze instability on visual thresholds. Later, Kothe and Regan (1990b) showed psychophysical evidence to differentiate between the effects of gaze instability and contour interaction on visual acuity measurements using a Regan repeat letter chart. This was later confirmed by Simmers, Gray and Winn (1999) who measured visual acuity using the Regan repeat letter chart and Glasgow acuity chart in subjects with normal vision and nystagmus patients. Though repeat letter charts show some promise in being able to differentiate visual acuity loss due to contour interaction or gaze instability, the spatial characteristics of repeat letter charts have not been described in any detail. Specifically, it is not known if the repeat letter charts that have been used previously (comprising 1.0 letter width separations) are sufficiently crowded to produce any contour interaction effects. Though the contour interaction effect has been widely studied in the past (Flom, Weymouth and Kahneman, 1963; Simmers, Gray, McGraw and Winn, 1999a), the stimuli used were targets surrounded by flanking bars, unlike repeat letter charts that have letters surrounded by letters simulating clinical vision charts. On the other hand, while crowding is described as due to contour interaction, gaze fixations and attention, to solely study the effect of contour interaction on crowding, factors such as gaze fixations and attention have to be constant. The repeat letter chart format may be a useful tool to systematically segregate the components of crowding and to solely study the effect of contour interaction on visual thresholds. Therefore, this study will investigate the effect of contour interaction on SGRL thresholds using a high contrast SGRL chart that is less sensitive to the effect of gaze instability and attention. Further, the effect of letter type on contour interaction will also be assessed.

Methods

Apparatus & Stimuli

The stimuli used in this study were the seven Sheridan-Gardiner (SG) letter optotypes A, T, H, O, U, X and V. These optotypes were originally selected as appropriate for use in a children’s vision chart because of their familiarity to young children and their inherent vertical symmetry (Sheridan and Gardiner, 1970), which lessens the potential for confusion based on laterality (unlike the Illiterate E or Landolt C charts which present a problem for some young children who confuse left and right). A subset of these optotypes, the H, O, T and V has also been used extensively in other pre-school vision tests (Hered, Murphy and Clancy, 1997). The individual letter optotypes were constructed based on a 5x5 stroke width size and presented on a high-resolution 21” monitor (Sony Multiscan GDM-F520) using a PC interface running Microsoft PowerPoint™. The size of each letter was 4.3mm ± 0.05mm measured directly off the monitor using a 7x magnifier and was approximately equivalent to a Snellen fraction of 6/3 at 6m. The mean luminance of the screen and letter targets were 121.1 cd /m^2 and 1.8 cd /m^2 respectively, yielding a Weber’s contrast of 80% (measured with PR-650 Spectrascan Telephotometer).

For most of the experiments described, we constructed and used a series of SGRL charts, based on the repeat letter chart design described elsewhere (see Kothe and Regan, 1990). The SGRL chart comprised a single SG letter repeated in an array totally 49 letters. These 7 x 7 arrays were produced for each of the SG letters (see Figure 2.1). The between letter separation of the arrays was based on the previous work on contour interaction (Flom, Weymouth and Kahneman, 1963) and varied through a range of different separations as a function of the letter size. The separations used were 1.0, 0.8, 0.6, 0.4, 0.2 times the test letter size and an abutting condition. Each of the SGRL charts was surrounded by an additional single letter array of randomly allocated SG letters making each array a dimension of 9 x 9 in total. The addition of the extra non-repeat SG letters was included to maintain equality of contour interaction for the outside repeated letters. The SGRL charts were presented at random in runs of 100 trials per separation condition. Each individual SGRL array and separation condition was presented at least 14 times per run. Experiments were conducted under normal room illumination.

Figure 2.1: Schematic depicting the range of SGRL stimuli used in the experiment. The stimuli consist of a repeated SG letter in a central 7 x 7 array. The outer surrounding optotypes are randomised SG letters on all four sides to maintain contour interaction for the outside repeated letters. For clarity, only one inter-letter separation (1.0 times the letter width) is shown.

```
H U A T O X V T H   H U A T O X V T H   H U A T O X V T H   H U A T O X V T H
U U U U U U U U X   U T T T T T T T X   U A A A A A A A X   U O O O O O O O X
T U U U U U U U T   T T T T T T T T T   T A A A A A A A T   T O O O O O O O T
O U U U U U U U A   O T T T T T T T A   O A A A A A A A A   O O O O O O O O A
X U U U U U U U X   X T T T T T T T X   X A A A A A A A X   X O O O O O O O X
V U U U U U U U H   V T T T T T T T H   V A A A A A A A H   V O O O O O O O H
A U U U U U U U A   A T T T T T T T A   A A A A A A A A A   A O O O O O O O A
H U U U U U U U O   H T T T T T T T O   H A A A A A A A O   H O O O O O O O O
A X V H T O X T U   A X V H T O X T U   A X V H T O X T U   A X V H T O X T U

H U A T O X V T H   H U A T O X V T H   H U A T O X V T H
U H H H H H H H X   U V V V V V V V X   U X X X X X X X X
T H H H H H H H T   T V V V V V V V T   T X X X X X X X T
O H H H H H H H A   O V V V V V V V A   O X X X X X X X A
X H H H H H H H X   X V V V V V V V X   X X X X X X X X X
V H H H H H H H H   V V V V V V V V H   V X X X X X X X H
A H H H H H H H A   A V V V V V V V A   A X X X X X X X A
H H H H H H H H O   H V V V V V V V O   H X X X X X X X O
A X V H T O X T U   A X V H T O X T U   A X V H T O X T U
```

Procedure

General condition

Six adult subjects with normal or corrected to normal visual acuity (of at least 6/6), normal binocular vision and who were free from ocular disease participated. The research followed the tenets of the Declaration of Helsinki and approval of the experimental protocol was obtained from the institutional Human Research Ethics Committee. Informed consent was obtained from all the subjects after the nature and consequences of the study were explained. Subjects viewed the monitor monocularly either directly or if required, through an optical quality front surface mirror and performed a single-interval forced choice task. SGRL charts were presented at 2 sec intervals. However, test duration was not a limiting factor. Subjects were required to identify the repeated letter in the central 7x7 array. No restriction was placed on where the subjects fixated within the array to make their decision. A method of constant stimuli was used where the size of the letters was varied by varying the test distance according to a logarithmic scale. Testing began at 6m and, based on the percentage correct responses, subjects were moved either closer to, or further from the monitor to cover a range of distances from the guess rate to 100% correct responses encompassing the psychometric function. The test distances ranged from 1.9m to 9.5m.

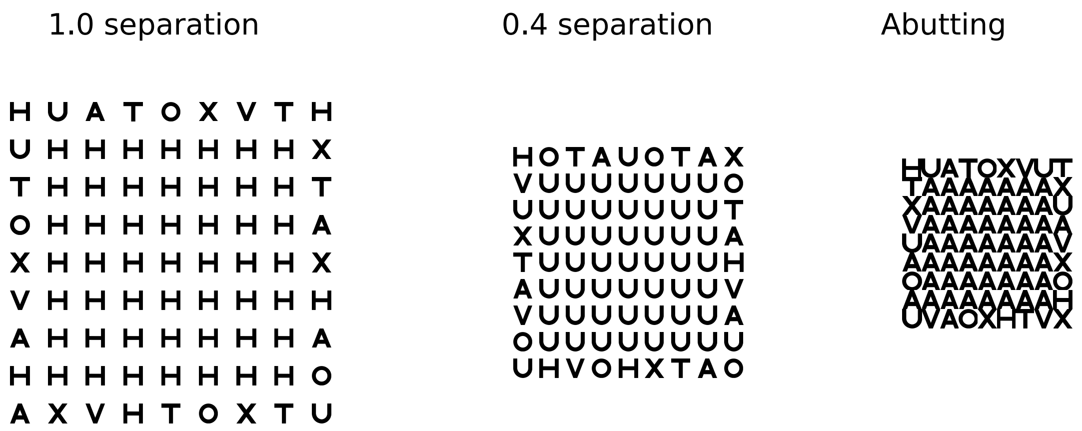
The proportion of correctly identified letters (percent correct) were recorded by an examiner for each letter separation condition beginning with the 1.0 letter width separation. The remaining separation conditions were presented at random within and between subjects. To prevent the possibility of small luminance cues influencing the response, repeat letter charts were displayed, at random, in five different positions; centrally and four other positions equidistant from the middle of the monitor. Subjects were given sufficient practice to obtain consistent results and breaks were allowed in between the runs to lessen fatigue. Each datum was the average of at least four runs of 100 trials.

Control conditions

In addition to the main experiment, two control conditions were carried out. In the first control condition, isolated (i.e., single letter) visual acuity was measured on 5 subjects chosen from the main experiment (one of the original subjects withdrew after the main experiment). The stimuli were the seven isolated SG letters and the procedure was the same as the main experimental condition.

As the inter-letter separation is reduced from the 1.0 letter separation to the abutting condition the overall array size of the SGRL chart is also reduced (Figure 2.2). In addition, varying the test distance from 1.9 m to 9.5 m also altered the total angular size of the repeat letter charts. The stimuli with a 7x7 letter array for the 1.0 letter width separation subtended approximately 166 x 166 and 33 x 33 min arc at 1.9 m and 9.5 m respectively. The stimuli with 7x7 letter array for the abutting condition subtended approximately 88 x 88 and 17 x 17 min arc at 1.9 m and 9.5 m respectively. Although the decrease in the angular size is unlikely to be a factor in performance, to be assured that this was the case, a second control experiment was performed using a SGRL chart but constructed with a 3 x 3 repeated array.

Figure 2.2: Schematic showing examples of the SGRL stimuli for the 1.0 letter width separation, 0.4 letter width separations and abutting conditions. For each separation condition, as the separation between the letters decreases the overall array size decreases.

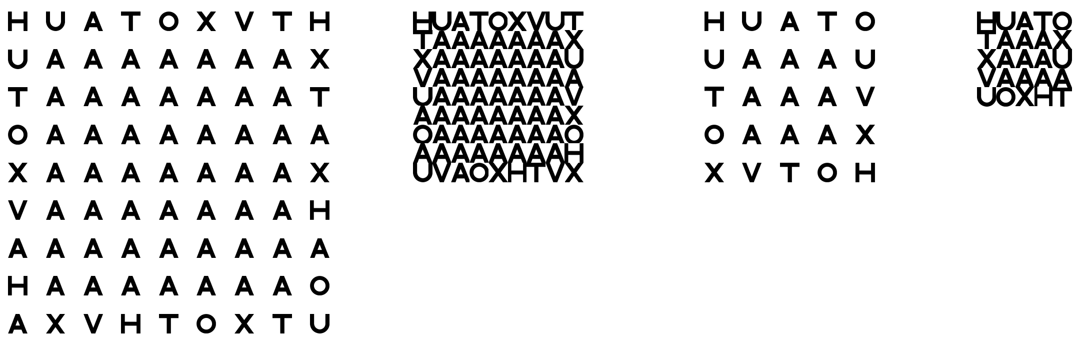


Three subjects from the main experiment participated in the second control condition. The 3x3 array stimuli consisted of a central 3x3 array of the same letters surrounded by an additional single letter array of randomly allocated SG letters to maintain equality of contour interaction for the outside repeated letters. The stimuli were constructed with two extreme separation conditions which covered the maximum and minimum array sizes, the 1.0 letter width separation and the abutting condition (see Figure 2.3). The angular subtense of the SGRL chart at the other separations (0.8 to 0.2 letter separations) will be within the two extreme separation conditions. The 3x3 letter array, 1.0 letter width separation, subtended approximately 88 x 88 and 17 x 17 min arc at 1.9 m and 9.5 m respectively. The 3 x 3 letter array, abutting condition, subtended approximately 48 x 48 and 10 x 10 min arc at 1.9 m and 9.5 m respectively

The procedure was the same as that used in the main experiment. A 3x3 repeat letter array with 1.0 letter width separation and abutting condition was presented at a range of the test distances. The subject's task was to identify the repeated letter presented in the central 3x3 array of letters. The results for the 7x7 array were taken from the main experiment. The visual thresholds for the 3x3 array, 1.0 letter width separation were compared to the 7x7 array, 1.0 letter width separation. Similarly, the thresholds for the 3x3 array, abutting condition were compared to the 7x7 array, abutting condition.

Figure 2.3: Schematic of the SGRL stimuli used in the second control condition which shows the 7 x 7 and 3 x 3 array sizes with inter-letter separation of 1.0 times the letter width and abutting condition.

7x7 1.0 7x7 abutting 3x3 1.0 3x3 abutting



Legibility

The effect of letter type on contour interaction including the effect of letter type of the isolated letter condition was also assessed by extracting the data from the main experimental results. The responses obtained from the main experiment were arranged in terms of letter type for each separation condition.

Data analysis

The percentages of correct responses obtained for each subject and each separation condition were entered into Microsoft Excel. The average of all the 4 runs and their standard deviations were obtained. The data thus obtained were entered into Igor Pro Software (Wavemetrics, Lake Oswego, Oregon, USA) and were fit using psychometric curves of the form of a Weibull function (Pelli, Robson and Wilkins, 1988) defined as:

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

Where p is the ratio of correct responses for a given letter size (x) in LogMAR units, g is the probability of correct responses equal to 1/n (where n is the number of the SG letters used, i.e. 7), and b and t represent the slope and threshold (approximating 68% performance) respectively. The thresholds and slopes thus obtained were entered into a standard statistical package SPSS for Windows, Release Version 16.0, (© SPSS, Inc., 2009, Chicago, IL, www.spss.com). A repeated measures ANOVA and post-hoc analysis using a Bonferroni test were performed as appropriate. F values were corrected by adjusting the degrees of freedom with Greenhouse-Geisser method for any violations of Mauchly's sphericity.

Results

General condition

Percentage correct responses were plotted as a function of visual acuity (LogMAR) and are shown in Figure 2.4. Each data set is fit by the psychometric curves described earlier and represented by different colours corresponding to the individual letter separations used in the experiment (1.0, 0.8, 0.6, 0.4, 0.2 letter width separations and abutting). The data for the isolated letter condition are also shown. There is a tendency for the functions to shift across to the right, reflecting the increasing difficulty in letter recognition as a function of decreasing letter separation (i.e. contour interaction). In most of the subjects, the extent of the shift in the psychometric curves in relation to the decreased performance was minimal from 1.0 to 0.4 letter width separation suggesting a limited effect of contour interaction. The shift in the psychometric curves towards poorer LogMAR reflects the deterioration in performance as the influence of contour interaction becomes more evident from the 0.2 letter width separation. The majority of the subjects had maximum deterioration in performance at the abutting condition. However, one subject (RS) had maximum deterioration in performance at the 0.2 letter width separation.

The effect of contour interaction on threshold visual acuity is shown in Figure 2.5 where the SGRL thresholds are plotted as a function of letter separation conditions. The thresholds in LogMAR units were derived from the psychometric functions for all the letter separations and the isolated letter condition. All subjects completed all of the experimental conditions with the exception of subject IH who withdrew without completing the isolated condition. In order to use his data the following procedure was followed to replace his missing isolated condition result. A t-test was performed on the data of the 5 subjects who completed all conditions for the isolated letter thresholds and thresholds obtained at 1.0 letter separation (t test, $p=0.94$). Since there was no significant difference between the isolated letter thresholds to 1.0 letter thresholds, the missing value of the isolated letter threshold for the subject IH was replaced by his 1.0 letter threshold value. The threshold values and their means are shown in Table 2.1(A). Figure 2.5(A) shows an increase in the recognition thresholds with decreased inter-letter separations. The thresholds for separations ranging between 1.0 to 0.4 letter widths including the isolated letter thresholds were nearly at a constant horizontal level and have similar threshold values. The thresholds started to increase at 0.2 letter separation. The maximum increase in the thresholds was at the abutting condition. Repeated measures within subjects one way ANOVA showed a significant effect of separation on recognition thresholds $F(1.96, 9.80) = 22.10$, $p < 0.01$. Pair wise comparisons showed no significant difference between the thresholds obtained for the isolated letter condition (-0.23 ± 0.03) and those obtained for 0.2 (-0.13 ± 0.09) to 1.0 letter width separations (-0.22 ± 0.7) ($p > 0.05$). However, a significant difference in thresholds was seen between the isolated letter (-0.23 ± 0.03) and abutting conditions (-0.05 ± 0.05). A significant difference was also seen between the abutting and rest of the separation conditions except for the 0.2 letter width separation.

Figure 2.4: The data shown in the figure are a layout of representative results of psychometric curves for each subject, at each separation condition (coloured lines) and the isolated letter condition (green fluorescent lines). Each datum shown represents the average of at least 400 trials at each test distance measured. Error bars represent ± 1standard deviation (SD).

Figure 2.5: (A) Recognition thresholds are plotted as a function of separation in letter widths. Each datum represents the recognition threshold for each separation averaged across all subjects. The error bars represents ±1 standard error (SE). (B) Normalised thresholds are plotted as a function of separation in letter widths. The histograms represent the recognition

thresholds normalised against the isolated letter threshold (threshold value at each separation - isolated letter threshold value) averaged across all the subjects. The error bars represent ±1 standard error (SE).

A

B

Table 2.1: (A) Depicts high contrast repeat letter thresholds for each individual subject obtained from the psychometric functions and the means of all the subjects for each separation condition. (B) Depicts normalised recognition thresholds for each individual subject obtained from the psychometric functions and the means of all the subjects for each separation condition.

A	Separation	**Abutting**		**0.2**		**0.4**		**0.6**		**0.8**		**1.0**		**Isolated**	
	Subjects	Threshold	Stdev	Threshold	Stdev	Threshold	Stdev	Threshold	Stdev	Threshold	Stdev	Threshold	Stdev	Threshold	Stdev
	SC	-0.05	0.01	-0.13	0.00	-0.18	0.00	-0.22	0.00	-0.28	0.00	-0.27	0.00	-0.23	0.00
	PP	0.05	0.01	-0.07	0.01	-0.14	0.00	-0.15	0.01	-0.16	0.00	-0.14	0.00	-0.17	0.00
	DD	-0.05	0.02	-0.13	0.01	-0.17	0.00	-0.25	0.01	-0.17	0.00	-0.15	0.01	-0.19	0.01
	VV	-0.10	0.01	-0.25	0.01	-0.26	0.00	-0.29	0.01	-0.31	0.00	-0.28	0.00	-0.25	0.01
	RS	-0.09	0.04	0.01	0.01	-0.23	0.01	-0.24	0.01	-0.30	0.01	-0.22	0.01	-0.22	0.01
	IH	-0.07	0.01	-0.20	0.00	-0.25	0.01	-0.29	0.01	-0.29	0.00	-0.30	0.00	-0.30	0.00
	Mean	**-0.05**		**-0.13**		**-0.21**		**-0.24**		**-0.25**		**-0.22**		**-0.23**	
	Std error	**0.05**		**0.09**		**0.05**		**0.05**		**0.07**		**0.07**		**0.05**	
B	Separation	**Abutting**		**0.2**		**0.4**		**0.6**		**0.8**		**1.0**		**Isolated**	
	Subjects	Normalized		Normalized		Normalized		Normalized		Normalized		Normalized		Normalized	
		thresholds		thresholds		thresholds		thresholds		thresholds		thresholds		thresholds	
	SC	0.19		0.10		0.05		0.01		-0.04		-0.03		0.00	
	PP	0.21		0.10		0.03		0.02		0.01		0.02		0.00	
	DD	0.14		0.06		0.02		-0.06		0.02		0.04		0.00	
	VV	0.15		0.00		-0.01		-0.04		-0.06		-0.03		0.00	
	RS	0.13		0.23		-0.01		-0.02		-0.08		0.00		0.00	
	IH	0.23		0.09		0.04		0.01		0.01		0.00		0.00	
	Mean	**0.18**		**0.10**		**0.02**		**-0.01**		**-0.02**		**0.00**		**0.00**	
	Std error	**0.04**		**0.07**		**0.03**		**0.03**		**0.04**		**0.03**		**0.00**	

Figure 2.5 (B) shows the data for the normalised thresholds plotted as a function of the letter separation. The normalised threshold values and their means are shown in Table 2.1 (B). The data were normalised in order to remove any differences in the results, which may have been due to the different baseline visual acuity scores of each subject. Threshold values greater than zero indicate threshold elevation. The threshold values for separations greater than zero and significantly different indicate contour interaction. Threshold values less than zero indicate threshold reduction. Threshold values for separations less than zero and significantly different indicate facilitation. A decrease in the thresholds and facilitation was noticed for the 1.0 to 0.6 letter width separation (below the horizontal line). Threshold elevation was noticed for 0.4, 0.2 letter width separation and abutting condition. However, the threshold elevation for 0.4 and 0.2 letter separation was not significantly different from the other separations including the isolated letter condition i.e. from 0 ($p > 0.05$). A significant threshold elevation was observed only at the abutting condition ($p < 0.01$). The results suggest that contour interaction started to increase from 0.2 letter width separation though not statistically significant. We assume that the large variance may have led to non-statistical significant threshold at the 0.2 letter separation. The maximum contour interaction was at the abutting condition.

Further, the slopes obtained from the psychometric curve fitting plotted as a function of separation are shown in Figure 2.6. A correction was applied as previously described to obtain a value for the missing data for subject IH. As the t-test between the slope values of the isolated letter to 1.0 letter separation showed no significant difference for the 5 subjects (t test, $p = 0.77$), the missing slope value for the isolated letter condition for the subject

IH was replaced by his slope value at 1.0 letter separation. The slope values and their means are shown in the Table 2.2. The slopes for separations ranging between 1.0 to 0.4 letter widths including the slope value for the isolated letter were nearly constant with similar slope values. The slope value decreased at 0.2 letter separation. The shallowest slope occurred at the abutting condition. Repeated measures within subjects one way ANOVA showed a significant effect of separation on slopes $F(2.11, 10.56) = 17.11$, $p < 0.01$. Pair wise comparisons showed that the slope values from 0.2 (5.42 ± 0.85) to 1.0 letter width separation (6.33 ± 0.96) were not significantly different from the isolated slope value (6.49 ±1.30) ($p > 0.05$). A significant difference in slopes was seen between all the separations and the abutting condition (2.95 ± 0.99) ($p < 0.01$). Further, Figure 2.4 showed that the psychometric curves for separations ranging from 1.0 to 0.2 letter separation including the isolated letter condition were steep while the psychometric curves for the abutting condition was flatter than the rest of the separations.

Figure 2.6: Average slope of the psychometric functions is plotted as a function of separation in letter width. Each datum represents the mean slope value averaged across all the subjects and for each of the separation condition. The error bars represent ±1 SE.

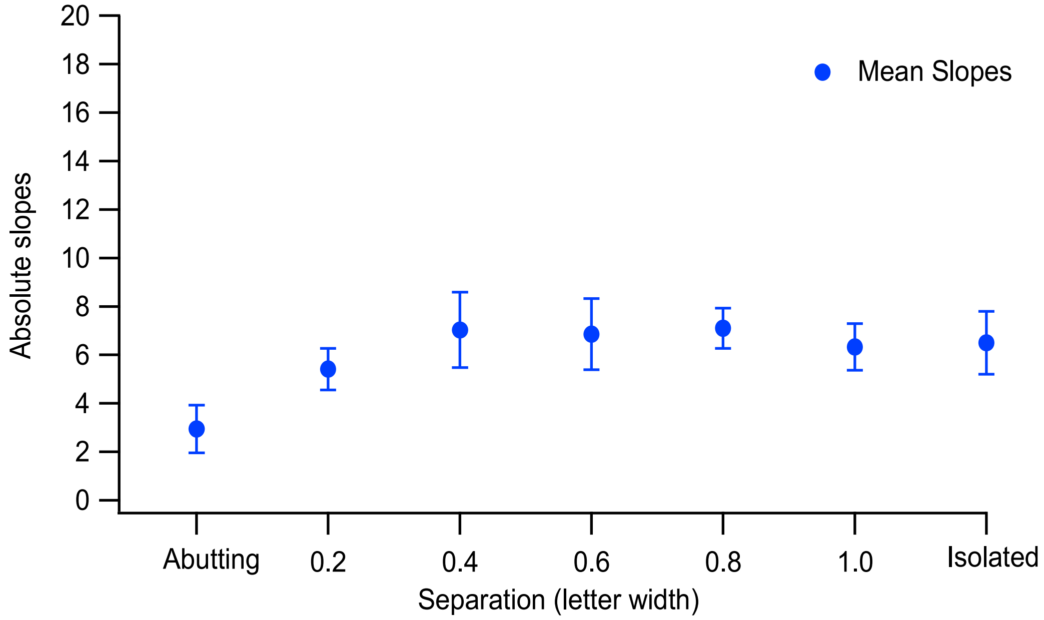


Table 2.2: Depicts slopes obtained from the psychometric functions for each individual subject and the means of all subjects for each separation condition and isolated letter condition.

Separation	**Abutting**		**0.2**		**0.4**		**0.6**		**0.8**		**1.0**		**Isolated**	
Subjects	Slope	Stdev	Slope	Stdev	Slope	Stdev	Slope	Stdev	Slope	Stdev	Slope	Stdev	Slope	Stdev
SC	3.58	0.26	5.64	0.37	7.15	0.37	9.01	1.03	8.16	0.34	7.88	0.55	7.12	0.55
PP	4.53	0.52	6.23	0.63	9.50	0.55	6.81	0.68	7.28	0.63	6.14	0.58	8.39	0.80
DD	2.13	0.30	6.15	0.94	5.88	0.24	7.66	0.92	7.87	0.83	6.53	1.00	6.05	0.91
VV	2.52	0.24	5.35	0.61	8.11	0.86	6.52	0.78	5.97	0.28	5.20	0.27	6.23	0.75
RS	1.90	0.39	3.89	0.45	6.25	1.50	4.55	0.55	6.55	0.63	5.51	0.64	4.45	0.49
IH	3.02	0.33	5.25	0.29	5.29	0.70	6.58	0.97	6.74	0.48	6.72	0.45	6.72	0.45
Mean	**2.95**		**5.42**		**7.03**		**6.86**		**7.09**		**6.33**		**6.49**	
Std error	**0.99**		**0.85**		**1.56**		**1.47**		**0.83**		**0.96**		**1.30**	

Control condition

The percentages of correct responses were plotted as a function of visual acuity (LogMAR) (Figure 2.7). Each data set was fit by the psychometric curves described earlier (Weibull functions) and represented by different colours corresponding to different separations (1.0 letter width separation and abutting condition) and array sizes (7x7 and 3x3). Figures 2.8 (A & B) show the thresholds and slopes respectively derived from the psychometric functions and plotted as a function of the array size and separation. A one factor within subjects ANOVA showed no significant effect of the array size on thresholds for both 1.0 letter width separation condition $F(1, 2) = 7.27$, $p > 0.05$ or the abutting condition $F(1, 2) = 17.5$, $p > 0.05$. Further, there was no significant effect of the array size on the slopes of the psychometric functions for both 1.0 letter width separation $F(1, 2) = 0.46$, $p > 0.05$ and abutting condition $F(1, 2) = 4.15$, $p > 0.05$. This shows that the mean recognition thresholds for 1.0 letter separation, 3x3 array size (-0.30 ± 0.02) was not significantly different to 1.0 letter separation, 7x7 array size (-0.26 ± 0.04). The recognition thresholds for the abutting condition, 3x3 array size (-0.13 ± 0.01) were not significantly different to abutting condition, 7x7 array size (-0.09 ± 0.02) (Table 2.3 A). Further, the slope values for 1.0 letter separation, 3x3 array size (5.96 ± 0.57) were not significantly different to 1.0 letter separation, 7x7 array size (5.81± 0.80). The slope values for the abutting condition, 3x3 array size (3.41 ± 1.22) were not significantly different to the abutting condition, 7x7 array size (2.52 ± 0.52) (Table 2.3 B).

Figure 2.7: The data shown are a layout of representative results of all the three subjects. The percentages of correct responses are plotted as a function of visual acuity. Each psychometric curve denoted by different colour represents the percentage of correct responses for 3x3 and 7x7 array at the abutting and 1.0 letter width separation for each subject individually. Each datum shown represents the average of at least 400 trials at each test distance measured. Error bars represent ± 1SD.

Figure 2.8: Absolute thresholds in LogMAR units (A) and slopes (B) are plotted as a function of array sizes (7 x 7 and 3 x 3 array) and separations (abutting and 1.0 letter width separation). The histograms shown below represent mean recognition thresholds (A) and mean slopes (B) for each array and separation condition. Error bars represent ± 1SE.

A

B

Table 2.3: (A) Depicts recognition thresholds for each individual subject and the means obtained for separations (1.0 letter width and abutting) and repeated letter array conditions (7x7 and 3x3). (B) Depicts slopes for each individual subject and the means obtained for separations (1.0 letter width and abutting) and repeated letter array conditions (7x7 and 3x3).

Separation & Array size	**Abutting 7x7**			**Abutting 3x3**			**1.0 7x7**			**1.0 3x3**	
A	Threshold	Stdev		Threshold	Stdev		Threshold	Stdev		Threshold	Stdev
IH	-0.07	0.01		-0.13	0.01		-0.30	0.00		-0.31	0.00
VV	-0.10	0.01		-0.13	0.01		-0.28	0.00		-0.31	0.01
RS	-0.10	0.04		-0.14	0.02		-0.22	0.01		-0.28	0.01
Mean	**-0.09**			**-0.13**			**-0.26**			**-0.30**	
Std error	**0.02**			**0.01**			**0.04**			**0.02**	
Separation & Array size	**Abutting 7x7**			**Abutting 3x3**			**1.0 7x7**			**1.0 3x3**	
B	Slope	Stdev		Slope	Stdev		Slope	Stdev		Slope	Stdev
IH	3.02	0.33		4.78	0.59		6.72	0.45		6.59	0.61
VV	2.56	0.24		3.00	0.45		5.20	0.27		5.81	0.73
RS	1.99	0.42		2.45	0.51		5.51	0.64		5.49	0.39
Mean	**2.52**			**3.41**			**5.81**			**5.96**	
Std error	**0.52**			**1.22**			**0.80**			**0.57**	

Legibility

The data for analysing the legibility of the letters were obtained from the data of the general condition. The percentages of correct responses are plotted as a function of letter size and are shown in Figures 2.9, 2.10, 2.11, 2.12, 2.13 and 2.14. Each figure represents the data for each of the five subjects. Data for subject IH was not included in the legibility analysis. For all the subjects, the psychometric functions of each SG letter for separations 1.0 to 0.4 letter width were steep and narrowly placed, while the psychometric functions for the 0.2 letter separation and abutting were more widely displaced.

Figures 2.9, 2.10, 2.11, 2.12, 2.13: Depicts the legibility data representing a layout of the percentage correct responses plotted as a function of letter size (LogMAR). Each datum represents 56 to 60 presentations obtained from the 4 runs that were obtained from the data of the general condition. Each psychometric curve represented by a different colour corresponds to the percentage correct for each SG letter at each separation condition. The error bars represents ± 1 SD.

Figure 2.9:

Figure 2.10:

Figure 2.11

Figure 2.12:

Figure 2.13:

Figure 2.14: The data shown represent a layout of letter legibility for the isolated SG letter condition for 5 subjects. The percentages of correct responses are plotted as a function of visual acuity. Each psychometric function is denoted by a different colour representing percentage correct responses for each of the 7 isolated SG letters and for each subject. The

error bars represent ± 1 SD.

The effect of the relative letter legibility on contour interaction can be precisely obtained by comparing the thresholds obtained from the psychometric curves at each separation condition (see Figure 2.15). The mean thresholds for each letter and separation condition (averaged across the five subjects) are shown in Table 2.4 (A). Letters T and H showed nearly the same thresholds for each separation condition measured. Letters T and H had lower thresholds and were easier to identify than other SG letters at all the separations measured. The data points for the SG letter thresholds were closely spaced for the isolated letter condition and separations ranging from 1.0 to 0.4 letter separation. The SG letter thresholds for the 0.2 letter separation and abutting were more widely spread along the vertical axis.

A two factor within subject factorial ANOVA was performed for the letter separation and letter type. There was a significant main effect of letter type on recognition thresholds $F (2.39, 9.56) = 57.17$, $p < 0.01$ and a significant main effect of separation on recognition thresholds $F (1.99, 7.96) = 10.43$, $p < 0.01$. A significant interaction effect (letter separation and letter type) on recognition thresholds $F (2.19, 8.76) = 5.05$, $p < 0.05$ was also evident. Subsequently, the effect of letter type at each separation condition was considered separately. Repeated measures one way ANOVA showed a significant effect of letter type at each separation condition ($p< 0.01$). Further, repeated measures one way ANOVA showed no significant effect of letter type on separation for letters T [$F (2.87, 11.49) = 1.43$, $p > 0.05$] and H [$F (1.63, 6.51) = 0.81$, $p > 0.05$]. However, other SG letters (A, O, U, V, X) had a significant increase in the thresholds with decreased inter-letter separations. Repeated measures one way ANOVA showed a significant effect of letter type on separation for letters A [$F(2.16, 8.65) = 11.90$, $p < 0.01$], O [$F(1.22, 4.89) = 9.73$, $p < 0.05$], U [$F(2.34, 9.38) = 22.18$, $p < 0.01$], V [$F(1.99, 7.98) = 6.80$, $p < 0.05$] and X [$F(1.42, 5.69) = 13.97$, $p < 0.01$]. For letter type A, a significant difference in thresholds was evident between the 0.2 and 0.6 letter separations. For letter type O, a significant difference in thresholds was evident between the 0.4 and 0.6 letter separations. For letter type U, a significant difference in thresholds occurred between the abutting to 0.6, 0.8, 1.0 letter separations and isolated letter condition. For letter type V, a significant difference in thresholds was evident between the abutting and 0.6 letter separations. Finally for letter X, a significant difference in thresholds was evident between the abutting to 1.0 letter separations and the isolated letter condition.

Figure 2.15: The graph shows mean legibility results across the five subjects. Threshold (LogMAR) is plotted as a function of separation in letter widths. Each datum represents the mean threshold values for each of the seven SG letters for each separation and isolated letter condition. Each letter is represented by one individual colour for each of the separations used.

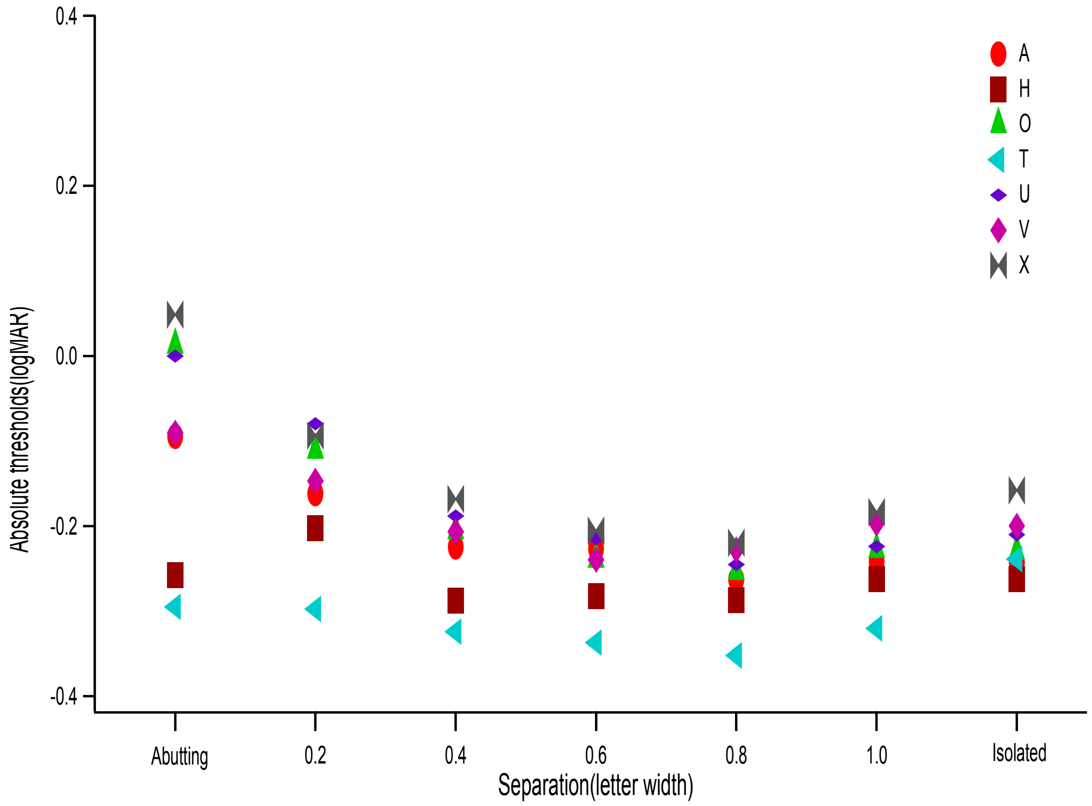


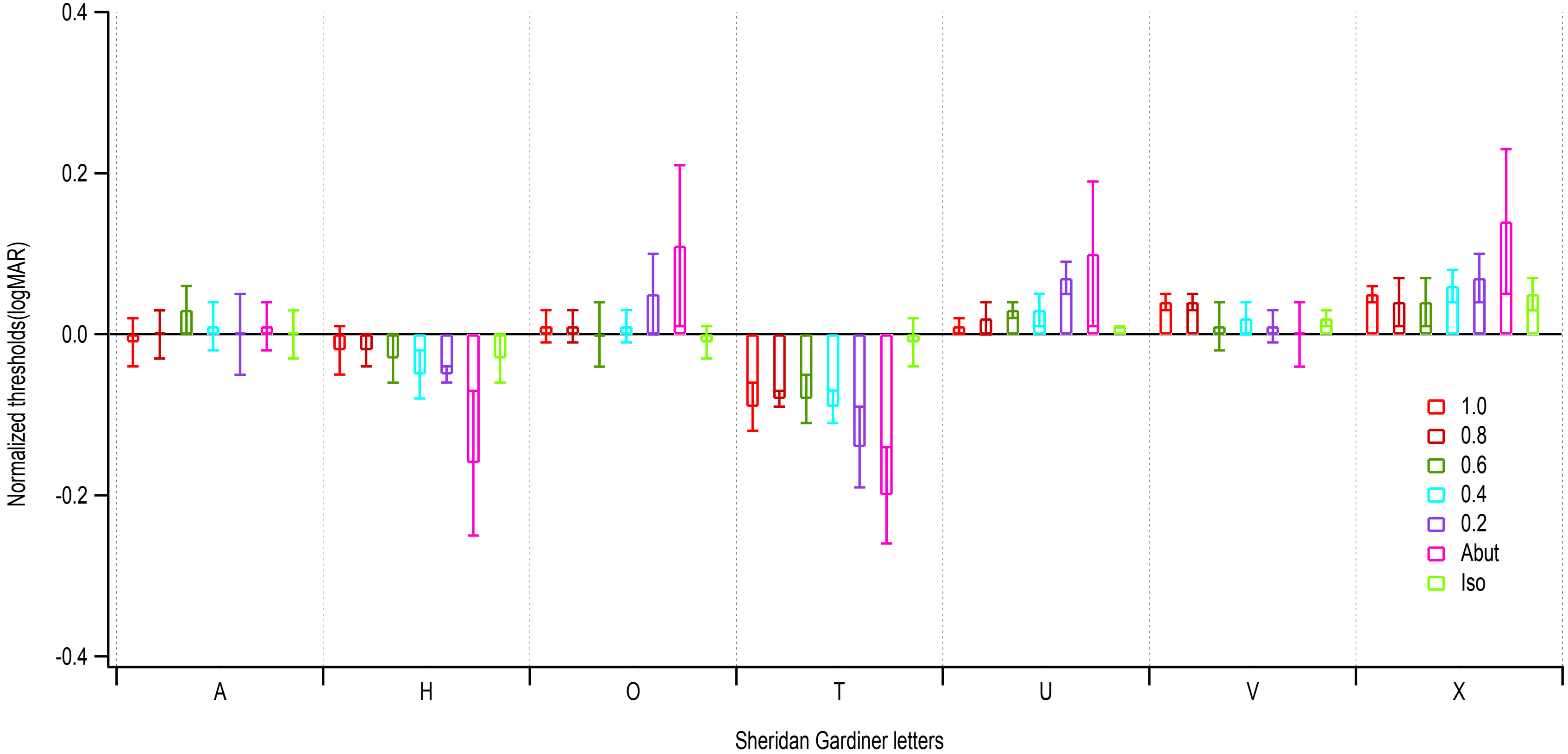
Table 2.4: Depicts the mean legibility thresholds (A) and normalised mean legibility thresholds (B) of five subjects obtained for each separation condition and each of the SG letters.

A	**Abutting**		**0.2**		**0.4**		**0.6**		**0.8**		**1.0**		**Isolated**	
	Mean Threshold	Std error	Mean Threshold	Std error	Mean Threshold	Std error	Mean Threshold	Std error	Mean Threshold	Std error	Mean Threshold	Std error	Mean Threshold	Std error
A	-0.09	0.11	-0.14	0.07	-0.21	0.06	-0.21	0.06	-0.25	0.09	-0.23	0.08	-0.24	0.07
H	-0.26	0.16	-0.16	0.07	-0.27	0.07	-0.26	0.07	-0.28	0.08	-0.24	0.08	-0.26	0.03
O	0.01	0.12	-0.09	0.11	-0.20	0.05	-0.23	0.05	-0.24	0.06	-0.21	0.06	-0.23	0.03
T	-0.29	0.12	-0.28	0.11	-0.31	0.05	-0.32	0.07	-0.34	0.08	-0.31	0.08	-0.24	0.05
U	0.00	0.07	-0.07	0.10	-0.18	0.05	-0.20	0.06	-0.24	0.08	-0.21	0.07	-0.21	0.04
V	-0.09	0.10	-0.13	0.08	-0.19	0.05	-0.23	0.05	-0.21	0.07	-0.18	0.06	-0.20	0.04
X	0.05	0.07	-0.07	0.11	-0.16	0.06	-0.20	0.06	-0.22	0.08	-0.17	0.07	-0.16	0.03
B	**Abutting**		**0.2**		**0.4**		**0.6**		**0.8**		**1.0**		**Isolated**	
	Mean normalized threshold	Std error	Mean normalized threshold	Std error	Mean normalized threshold	Std error	Mean normalized threshold	Std error	Mean normalized threshold	Std error	Mean normalized threshold	Std error	Mean normalized threshold	Std error
A	0.01	0.03	0.00	0.05	0.01	0.03	0.03	0.03	0.00	0.03	-0.01	0.03	0.00	0.03
H	-0.16	0.09	-0.05	0.01	-0.05	0.03	-0.03	0.03	-0.02	0.02	-0.02	0.03	-0.03	0.03
O	0.11	0.10	0.05	0.05	0.01	0.02	0.00	0.04	0.01	0.02	0.01	0.02	-0.01	0.02
T	-0.20	0.06	-0.14	0.05	-0.09	0.02	-0.08	0.03	-0.08	0.01	-0.09	0.03	-0.01	0.03
U	0.10	0.09	0.07	0.02	0.03	0.02	0.03	0.01	0.02	0.02	0.01	0.01	0.01	0.00
V	0.00	0.04	0.01	0.02	0.02	0.02	0.01	0.03	0.04	0.01	0.04	0.01	0.02	0.01
X	0.14	0.09	0.07	0.03	0.06	0.02	0.04	0.03	0.04	0.03	0.05	0.01	0.05	0.02

Normalised recognition thresholds (recognition letter threshold at each separation condition – mean threshold for all the 7 SG letters for each separation conditions) were obtained for each separation condition and averaged across all subjects (see Table 2.4 B). The normalization procedure was similar to that obtained from the results of Plainis, Tzatzala, Orphanos and Tsilimbaris (2007). The normalised thresholds for the letters T and H fall below the mean normalised threshold line and were easy to identify at all the separation conditions (see Figure 2.16). The normalised threshold values for letters A, O, V, U and X fall on or above the mean threshold line representing increase in the thresholds. The order of the normalised legibility of letters averaged across all the subjects and for each separation condition is described below.

Abutting	T > H > V > A > U > O > X
0.2	T > H > A > V > O > X > U
0.4	T > H > A > O > V > U > X
0.6	T > H > O > V > A > U > X
0.8	T > H > A > O > U > X > V
1.0	T > H > A > O > U > V > X
Isolated	H > O > T > A > U > V > X

Figure 2.16: Depicts the normalised thresholds plotted for each of the SG letters. Histograms represent the visual acuity thresholds normalised against the mean letter threshold (Recognition letter threshold at each separation – mean threshold for all the 7 letters for each separation condition). The error bars represents ± 1 SE.



Discussion

The main results of this study, which are consistent with previous work, show that visual acuity measured using repeat letter charts is reduced as inter-letter separation decreases. As repeat letter charts are immune to any potential instability in eye movements that may contribute to the crowding effect, the present results reflect the influence of contour interaction. The magnitude of the contour interaction effect was maximal for the abutting condition and threshold elevation was also evident at 0.4 and 0.2 letter inter-letter separations albeit not significantly different to the isolated letter condition.

Several previous studies have determined the intensity and extent of contour interaction using a Landolt C optotype surrounded by flanking bars (Flom, Weymouth and Kahneman, 1963; Hess and Jacobs, 1979; Manny, Fern and Loshin, 1987; Hess, Dakin, and Kapoor, 2000; Liu, 2001; Danilova and Bondarko, 2007) or letters surrounded by flanking bars (Simmers, Gray, McGraw and Winn, 1999a; Schlenker, Christakis and Braga-Mele, 2010). Some other studies used Landolt C, Tumbling E and gratings as both target and flankers (Danilova and Bondarko, 2007; Bondarko and Semenov, 2005). Some previous research has shown that the intensity of contour interaction at the fovea was maximal at a critical separation of 0.7 to 2 bar (stroke) widths (0.15 to 0.4 optotype width separations) in normal subjects (Flom, Weymouth and Kahneman, 1963; Manny, Fern and Loshin, 1987). However, this was not always the case and studies showed maximum contour interaction for foveal vision for abutting conditions (Flom, Weymouth and Kahneman, 1963; Jacobs, 1979; Wolford and Chambers, 1984; Manny, Fern and Loshin, 1987; Hess, Dakin, Kapoor and Tewfik, 2000; Danilova and Bondarko, 2007). The results of the present study show no significant effect of contour interaction between 0.2 to 1.0 letter width separations and the maximum effect was at the abutting condition. The variation in the extent and intensity of contour interaction in different studies is likely to be due to the differences in the experimental paradigms. This is because, the data of Alexander, Xie and Derlacki (1997) showed that the identification of letters was differently influenced when the percentage correct responses were measured at near thresholds or if the letter thresholds were derived from the psychometric functions.

Investigating the effect of contour interaction has mostly been addressed using optotypes surrounded by flanking bars (Flom, Weymouth and Kahneman, 1963; Jacobs, 1979; Hess and Jacobs, 1979; Manny, Fern and Loshin, 1987; Hess, Dakin, Kapoor and Tewfik, 2000; Liu, 2001). On the other hand, the effect of contour interaction has also been studied using optotypes in the form of trigrams or arranged in linear arrays (Taylor and Brown, 1972; McGraw and Winn, 1993; Liu and Arditi, 2001). However, the linear array target introduces both the effect of contour interaction and a potential instability in gaze fixations leading to studying the effect of crowding rather than the effect of contour interaction. However, the stimulus used in the present study is different, based on the fact that it is a SGRL chart design with letters surrounded by the same letters. The SGRL acuity is less sensitive to any effect of gaze fixations or any attentional components and visual acuity is therefore influenced by contour interaction only.

Since the experiment of Flom, Weymouth and Kahneman (1963) several hypotheses have been proposed to explain the phenomenon of crowding and contour interaction (Levi, 2008). Previous studies have attributed contour interaction to be of neural origin (Flom, Weymouth and Kahneman, 1963), due to the excitatory and inhibitory connections in the visual cortex (Polat and Sagi, 1994), due to the physical characteristics of the stimuli (Hess, Dakin and Kapoor, 2000), due to change in the amplitude difference spectrum of the stimuli (Liu, 2001) or due to target flanker similarity (Kooi, Toet, Tripathy and Levi, 1994; Nazir, 1992; Bernard and Chung, 2011). A number of recent studies have modelled crowding based on pooling, grouping or averaging of the target flanker signals (Parkes, et al., 2001; Levi, Klein and Hariharan, 2002; Pelli, Palomares and Majaj, 2004; Greenwood, Bex and Dakin, 2009; Dakin, Cass, Greenwood and Bex, 2010) or a form of feature integration of the target and flankers (Pelli, Palomares and Majaj, 2004; Nandy and Tjan, 2007; Bernard and Chung, 2011). However, regardless of the neural origin or physical attribution of the crowding effect, our results using repeat letter charts, which are immune to any instability in gaze fixations, show that contour interaction still occurs even when the ‘crowding’ stimuli are identical to one another.

Our results are similar to the recent studies by Danilova and Bondarko (2007). Though the stimulus used by Danilova and Bondarko (2007) was not a repeat letter chart design, the effect of contour interaction was studied using a stimulus that had the same target and flankers, similar to the present study. In addition, Danilova and Bondarko (2007) also studied the effect of contour interaction using Landolt C surrounded by flanking bars which is similar to the classic contour interaction experiment (Flom, Weymouth and Kahneman, 1963). Danilova and Bondarko (2007) showed that when Landolt C was surrounded by flanking bars, the intensity of interaction was at 1-2 bar widths (0.2 – 0.4 optotype width separation). On the other hand, when target and flankers were the same (i.e. when a Landolt C was surrounded by C's or a tumbling E target was surrounded by E's, the maximum contour interaction occurred at the abutting condition). Our results are in agreement with the findings of Danilova and Bondarko (2007) where maximum interaction occurred when target and flankers were abutting.

Conversely, our results are different to the classic contour interaction experiment by Flom, Weymouth and Kahneman (1963) and this difference could be attributed to the type of the stimuli used. Flom, Weymouth and Kahneman (1963) used a Landolt C and the task was to resolve the gap in C which is a resolution task. The flankers were bars which were different to the target C. Unlike the present experiment, a recognition task, which is different to a resolution task (Wittich, Overbury, Kapusta and Watanabe, 2006) and the target and flankers are SG letters. The stimuli used in the present study comprised a 7x7 array of letters and the resulting maximum interaction at the abutting condition could be a result of the stimuli resembling more of a pattern creating a camouflage effect that involve more noise from the flankers producing more contour interaction. Since the SGRL chart consists of a repeated letter target, we presume the involvement of greater inhibition and stronger interaction from the distracters based on the fact that dissimilar targets have weaker interaction (Polat and Sagi, 1993). While previous studies showed that the target flanker similarity would increase the crowding effect (Nazir, 1992; Kooi, Toet, Tripathy and Levi, 1994; Bernard and Chung, 2011), we suspect that the greater contour interaction in repeat charts at closer separations may be due to an ambiguous percept of repeat letter stimuli due to the combination of similar features as a result of similarity between the target and flankers thereby creating a new target. Saarela, Westheimer and Herzog (2010) showed that crowding also depends on spacing regularity between the target and flankers leading to grouping of the stimuli, similar to what we would assume happens in the SGRL chart used in the present study.

In addition, previous studies compared visual acuity scores obtained using different vision charts in order to investigate for an ideal chart to measure visual acuity scores in terms of repeatability, validity and reliability of the chart but not to study the effect of contour interaction on visual acuity scores (Jones, Westall, Averbeck and Abdolell, 2003; McGraw, Winn, Gray and Elliott, 2000; Simmers, Gray and Spowart, 1997). However, Shah, Laidlaw, Brown and Robson (2010) studied the effect of crowding on visual acuity using a COMPlog charts at approximately 0.8, 0.5, 0.4 and 0.2 letter width separations. They found that an inter-letter separation of 2.5 stroke width (0.5 letter width) had increased the sensitivity of the chart. They suggested that a 0.5 letter width separation would be an ideal separation to be incorporated to measure visual acuity scores. In addition, previous studies showed that vision charts such as Cambridge crowding cards (Atkinson, et al., 1985), Glasgow acuity chart (McGraw and Winn, 1993) and compact reduced LogMAR charts (Laidlaw, Abbott and Rosser, 2003) has an inter-letter separation of 0.5 letter widths. The separation of 0.5 letter widths may be chosen based on Flom's results (Flom, Weymouth and Kahneman, 1963) who noticed that in normal adults, the intensity of contour interaction on visual thresholds was minimal for separations greater than 0.4 optotype width. However, Flom, Weymouth and Kahneman (1963) measured the effect of contour interaction using flanked Landolt C with minimal or absence of any effect of gaze fixations.

Further, previous studies have shown that the effect of contour interaction on visual thresholds varied with age and was greater in younger children than older children and adults (Semenov, Chernova and Bondarko, 2000; Bondarko and Semenov, 2005; Jeon, Hamid, Maurer and Lewis, 2010). In addition, Maraini, Pasino and Peralta (1963) showed that with a linear array of E's, the separation difficulty in normal and amblyopic adults was at 1.0 optotype width separation. Flom, Weymouth and Kahneman (1963) found crowding with a complex interaction S chart that has 1.0 optotype separation. Both the stimuli (linear array of E's and complex interaction S chart) involved imposed gaze fixations to identify each optotype in the chart. Therefore, the effect of contour interaction on visual thresholds may vary depending on the presence or absence of gaze fixations. While it is known from previous studies that crowding is due to contour interaction and gaze instability (Stuart and Burian, 1962; Flom, Weymouth and Kahneman, 1963) and a repeat letter chart acts as a tool to segregate the components affecting crowding (Kothe and Regan, 1990b; Simmers, Gray, McGraw and Winn, 1999b), the results of the present study show that when the visual threshold is less sensitive to the effects of gaze instability and attention component, the extent of contour interaction using a SGRL chart occurs for separation less than 0.2 letter widths.

Additional support for the experiment in terms of any influence of the magnitude of gaze fixations within differentially subtended visual angles of the stimuli, caused due to the changes in the stimuli array sizes at different separation conditions and test distances is provided by the control experiment. There was no significant difference in the thresholds compared between the 3x3 and 7x7 array of letters for 1.0 letter width separation and abutting condition. This confirms that the 7x7 SGRL thresholds are not influenced by the effect of gaze instability. The relative distance magnification and thereby the visual acuity measurements may have not been affected by changing the test distance from far to close to the monitor. In addition, the effect of the letter type on contour interaction has also been analysed. Letters T and H were easy to identify at all the separations showing no effect of contour interaction for letters T and H. However, the remaining letters (A, O, U, V, X) showed contour interaction effect. The differences in the effect of letter type at different separation condition imply that letters T and H function differently to letters A, O, U, V and X. Gervais, Harvey and Roberts (1984) predicted letter confusion pairs between A-V, V-X, A-X and O-U. They also found that the letter T was confused with I and L where all the three letters has straight lines as their features. Reich and Bedell (2000) showed that the letters with curved features are more prone to confusion than the letters with straight lines. Further, a recent study has showed that the letters such as T and H creates space around or within the letters thereby reducing crowding between such letters (Fiset, et al., 2009). We assume this to be a reason for similar thresholds across separations for the letters T and H. These findings suggest the importance of consideration of equally legible letters while measuring visual acuity or contour interaction effect especially with H O T V chart and SG chart whose true visual acuity may be influenced by the differences in the legibility of letters.

Conclusion

These results suggest that the spatial extent and intensity of contour interaction varied in different experiments. The extent and intensity of contour interaction could vary depending on the type of the task involved and type of target and flankers. Further, the repeat letter acuity at different separation conditions may has been influenced by pattern recognition because of the repeated nature of the letters thus resulting in difference in the results between different studies. In addition, no significant difference in threshold was noticed between isolated letters and the SGRL chart at 1.0 letter width separation. While it is known that an isolated letter chart overestimates the relative visual acuity scores, charts with 1.0 letter width separation (such as Snellen and LogMAR chart) could also overestimate visual acuity if inter-letter separation is the only consideration. Further, the extent of contour interaction may vary depending on the presence or absence of gaze fixations. The contour interaction effect is also dependant on the letter type. This may have clinical implications when designing new children’s vision charts. It is therefore concluded that when visual thresholds are less sensitive to gaze instability and attention component, the effect of contour interaction on SGRL thresholds occurs between 0.2 letter separation and abutting condition.

Chapter 3

The effect of contour interaction on low contrast SG repeat letters in subjects with normal vision

Introduction

In the 2nd Chapter, the effect of contour interaction on visual acuity thresholds was investigated by using high contrast SGRL charts. The results showed that the extent of contour interaction started at 0.2 letter width separation, albeit non-significantly, reaching maximum intensity at the abutting condition. The high contrast SGRL thresholds were solely influenced by the effect of contour interaction. The present Chapter will determine the effect of contour interaction on low contrast SGRL acuity in subjects with normal vision.

Previous studies have investigated the effect of contrast on crowding (Kothe and Regan, 1990a; Giaschi, Regan, Kraft and Kothe, 1993). Crowding was greater for high contrast letters and less for the low contrast letters in subjects with normal vision. This was assumed to be due to greater interaction between the adjacent high contrast letters than the low contrast letters. However, variable crowding effects were noticed in subjects with amblyopic vision. Consequently, the findings of previous studies (Kothe and Regan, 1990a;

Giaschi, Regan, Kraft and Kothe, 1993) may not be explained solely by contour interaction as the Snellen type chart used in both the studies includes a combination of contour interaction, gaze fixation and attention components.

Simmers, Gray, McGraw and Winn (1999a) studied the effect of contrast (80% and 6%) on contour interaction in normal and amblyopic subjects using Sloan letters surrounded by flanking bars. They reported markedly reduced contour interaction with the low contrast stimuli in both the normal and amblyopic subjects. They suggested that contour interaction was reduced or absent under low contrast conditions.

The results from Chapter 2 showed that the contour interaction effect may depend on the relative letter type. Letters such as “T” and “H” that were relatively more legible exhibited minimal contour interaction across all the letter separation conditions. Previous studies also showed that the contrast will affect letter legibility (Alexander, Xie and Derlacki, 1997) and ultimately contour interaction (Simmers, Gray, McGraw and Winn, 1999a).

If as the available evidence suggests, that crowding is reduced under low contrast conditions, the expectation is that low contrast repeat charts would exhibit less contour interaction. This Chapter will investigate the effect of contour interaction on low contrast (5.8%) repeat letters in subjects with normal vision. The results will form the basis for comparison with the amblyopes data in Chapter 4.

Methods

Method of generating low contrast letters

The letter "O", one of the SG letters, was chosen as a representative letter to generate different levels of low contrasts. The outer circumference of the letter was positioned in the centre of the monitor (Sony Multiscan GDM-520) and the brightness and contrast levels were adjusted by using the "Format Picture" dialog box within Microsoft PowerPoint™. For each brightness and contrast level combination, three luminance readings of the screen and the target letter were taken (PR-650 Spectrascan Telephotometer). The average luminance of the screen (L_s) and the average luminance of the letter (L_t) were inserted into Weber's formula ($L_s - L_t / L_t$) to calculate the contrast of the letter (Table 3.1). Normal room illumination was used throughout the experiment and for all the measurements. The smallest target contrast that was perceptible on the screen was 5.8%. Herse and Bedell (1989) showed that visual acuity started to become affected (i.e. reduce) when the contrast of the target was less than approximately 20%. Also, previous investigators have used low contrast targets at 4.0% (Kothe and Regan, 1990a) and 6.0% (Simmers, Gray, McGraw and Winn, 1999a). Therefore, a contrast of 5.8% used in the present experiment should be sufficient to study the effect of low contrast on contour interaction.

Table 3.1: Depicts the stimuli contrasts for various combinations of the brightness/contrast levels

Brightness	Contrast	Luminance of Screen	Luminance of Target	Weber's Contrast
97	45	125	111	11.20%
97	40	124.67	111.67	10.43%
97	35	125	112.67	9.87%
97	30	124.67	113.67	8.82%
97	15	125	115.33	7.73%
97	10	125.33	117	6.65%
97	5	125.33	118	5.85%
99	40	125	121	3.20%
99	35	125.33	121.67	2.93%

Apparatus & Stimuli

The apparatus and stimuli were the same as those described in Chapter 2 except for the following: The dimension of each letter was fixed at approximately 8.6mm, measured with a 7x magnifier, approximately equivalent to a 6/6 letter size at 6m. A size adjustment was required because, the low contrast letters were more difficult to discern relative to the high contrast letters used in the experiment described in Chapter 2. Low contrast letters (5.8%) were used to design a SGRL chart at different letter width separations (1.0, 0.8, 0.6, 0.4, 0.2 and abutting). Each chart comprised a low contrast SG letter arranged in a 7X7 array surrounded by a linear array of random low contrast SG letters (Figure 3.1). The SGRL charts were presented at random in runs of 100 trials per separation condition. Each individual SGRL array and separation condition was presented at least 14 times per run.

Figure 3.1: Example of the low contrast SGRL stimuli at 1.0 letter width separation, 0.4 letter width separation and abutting condition.

1.0 Spacing

0.4 Spacing

Abutting

Procedure

General condition

Four adult subjects (two subjects from the high contrast experiment described in Chapter 2 and two new subjects) with normal or corrected to normal visual acuity and binocular vision participated in the study. The procedure followed was the same as that described in Chapter 2. The experimental monitor was switched on for at least 1 hr before beginning the data collection to allow the monitor to get adapted to the heating characteristics. All subjects underwent sufficient practice to familiarise them with the task. Practice sessions used low contrast SGRL charts at 1.0 letter separation.

Subjects performed a single interval forced choice task. The method of constant stimuli was employed whereby the size of the optotypes was changed by varying the viewing distance according to a logarithmic scale. The test distance for the study ranged from 1.9m to 8.5m. A chin rest was used to minimise any effects of instability in head position. Subjects viewed the monitor monocularly either directly or, if required, through an optical quality front surface mirror. SGRL charts were presented at 2 sec intervals. The stimuli were presented in five different positions; centrally and at 4 other positions equidistant from the middle of the monitor. The position of the target was varied to avoid any potential luminance cues. The subject’s task was to identify the repeated low contrast letter within the array. The responses were recorded by an examiner. The order of presentation of the stimuli was randomised within and between the subjects. For each letter separation condition, the percentage correct responses were determined at 5 to 6 test distances (ranging from guess rate to 100% correct responses). The procedure was repeated 4 times over a two day period and the average and standard deviation (SD) of these values were used to plot the psychometric functions.

Control conditions

In addition to the main experiment, two control conditions were done.

1. Percentage correct responses for a range of test distances were measured using isolated low contrast (5.8%) SG letters. The dimension of each letter was fixed at approximately 8.6mm as in the main experimental condition. The subject's task was to identify the letter presented which could appear in any one of the 5 positions, in the middle of the monitor and in the 4 quadrants equidistant from the middle of the monitor. The low contrast isolated letter threshold was compared to the low contrast repeat letter thresholds at six separation conditions in order to determine the effect of contour interaction.

2. A second control experiment was performed using low contrast (5.8%) isolated SG letters of size approximately 8.6mm but presented with a highly visible pre-cue stimulus of the same size as the letter. The pre-cue experiment was carried out to assess if the low contrast of 5.8% has affected the visibility of the isolated letter and consequently its location on the screen. Uncertainty about the target location could potentially increase the search time leading to more erratic and inaccurate eye movement patterns possibly affecting the recognition threshold and contour interaction.

The pre-cue condition consisted of a solid black square block of 80% contrast approximately 8.6mm in width. The pre-cue block and the low contrast isolated letter were not on the same slide in order to avoid any perceptual interaction and decreased attention due to the pre-cue block. The low contrast isolated letter slide was added as a separate slide after each pre-cue slide. The pre cue slide was presented first and secondly the isolated letter slide. The low contrast isolated letter in each slide was located at a position of about 2 letter width separation to the right side of the preceding pre-cue block. The subjects were informed to fixate at 2 letter width separation to the right side of the pre-cue block but not on the pre-cue block. This gave an opportunity for the subjects to fixate at the position where the low contrast letter would be displayed. Both the pre-cue and the low contrast isolated letter slides were presented for 2 sec each, as in the main experimental and the 1st control condition. Unlike the no pre-cue isolated letter condition, more time was available to perceive the pre-cue isolated low contrast letter, as the search time was reduced. Each run consisted of 200 experimental slides with alternating pre-cue slides and low contrast isolated letter slides. In addition, break slides were incorporated after every 50 slides where subjects could take a break thus alleviating fatigue. The procedure was the same as in the main experiment. The subjects had to identify the isolated pre-cue letter at different test distances sufficient enough to generate a psychometric function ranging from the guess rate to 100% correct responses.

Data analysis

Similar data analyses as described in Chapter 2 were employed. The percentage correct responses obtained for each subject and each separation condition were entered into Microsoft Excel. The data were fit in the form of psychometric curves with a Weibull function (Pelli, Robson and Wilkins, 1988) using Igor Pro Software (Wavemetrics, Lake Oswego, Oregon, USA) as described in Chapter 2. The descriptive parameters of each psychometric curve including its relative position along the abscissa (LogMAR), its threshold and slope provide important information on the effect of the low contrast on contour interaction. The thresholds and slopes obtained from the psychometric curves were used for statistical analysis SPSS for Windows, Release Version 16.0, (© SPSS, Inc., 2009, Chicago, IL, www.spss.com). A repeated measures ANOVA and post-hoc analysis using the Bonferroni test were performed as appropriate.

Results

General and control condition

Percentage correct responses were plotted as a function of visual acuity (LogMAR) and are shown in Figure 3.2. Each psychometric curve corresponds to a particular letter separation used in the experiment. In addition, the data for the isolated letter no pre-cue and pre-cue are shown in the same graphs.

The position of the curves can be used as a qualitative description of the performance level. For both RS and VV, the psychometric curves representing the separations ranging from 1.0 to 0.2 letter width were grouped together. This indicated that there was little difference in the ability to identify the low contrast SG letters at these separations. The psychometric curve for the abutting condition was shifted to the right. This suggests that the identification of the letters was difficult at the abutting condition i.e. the LogMAR visual acuity was poor when compared to the rest of the separation conditions. For subjects KB and UD, the psychometric curves were again grouped together with only a hint of the abutting curves being shifted to the right. For subject VV, the identification of the isolated letter was poorer than the other letter separations.

Figure 3.2: The data shown in the figure are a layout of representative results of psychometric curves for each individual subject at each separation condition and the isolated no pre-cue and pre-cue letter condition. Each datum shown represents the average of at least 400 trials at each test distance measured. Error bars represent ± 1SD.

Threshold of psychometric functions

The threshold LogMAR acuity was derived at a point on the psychometric curve corresponding to 68% correct. The individual and mean recognition thresholds for each separation condition and for all the subjects are shown (Table 3.2). In Fig 3.3 (A) the mean recognition thresholds are plotted as a function of the letter separation. The maximum increase in the threshold was at the abutting condition. The error bars were smaller at the isolated letter condition, signifying similar threshold values between the subjects at this condition. Surprisingly, the isolated letter thresholds for the no pre-cue condition was higher (albeit not significantly) than at any other separation condition except at the abutting condition. This finding was unexpected and different from that obtained with the high contrast letters (Chapter 2). Further, there was a slight reduction in the mean isolated pre-cue threshold when compared to the isolated no pre-cue condition. However, the mean isolated pre-cue threshold was still higher than the threshold values obtained at the other letter separation conditions except at the abutting condition. A 2 tailed paired t-test showed no significant difference in the thresholds between the isolated no pre-cue and pre-cue letter conditions ($p > 0.05$). As there was no significant difference between the no pre-cue and pre-cue isolated letter thresholds, the no pre-cue data were replaced by the pre cue data in further analysis. Repeated measures within subjects one way ANOVA showed a significant effect of separation on the low contrast recognition thresholds $F (1.47, 4.39) = 8.34$, $p < 0.05$. Pair wise comparisons showed a significant difference in thresholds for the abutting (0.25 ± 0.10) and 0.8 letter width separation (0.05 ± 0.04).

Table 3.2: (A) Depicts low contrast repeat letter thresholds for each individual subject obtained from the psychometric functions and the means of all the subjects for each separation condition including pre-cue and no pre-cue isolated letter condition. (B) Depicts normalised recognition thresholds for each individual subject obtained from the psychometric functions and the means of all the subjects for each separation condition.

A																
Separation	Abutting		0.2		0.4		0.6		0.8		1.0		Isolated		Isolated Pre Cue	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
RS	0.38	0.02	0.15	0.01	0.11	0.01	0.08	0.01	0.08	0.01	0.13	0.01	0.24	0.00	0.22	0.01
VV	0.17	0.01	0.06	0.01	-0.01	0.01	-0.01	0.01	0.03	0.01	0.04	0.01	0.27	0.01	0.11	0.01
KB	0.17	0.01	0.18	0.00	0.08	0.01	0.10	0.01	0.00	0.01	0.18	0.01	0.18	0.00	0.10	0.01
UD	0.27	0.02	0.21	0.02	0.12	0.01	0.19	0.01	0.09	0.02	0.20	0.01	0.18	0.01	0.20	0.02
Mean	**0.25**		**0.15**		**0.08**		**0.09**		**0.05**		**0.14**		**0.22**		**0.16**	
Std error	**0.10**		**0.06**		**0.06**		**0.08**		**0.04**		**0.07**		**0.05**		**0.06**	
B																
Separation	Abutting		0.2		0.4		0.6		0.8		1.0		Isolated		Isolated Pre Cue	
Subjects	Normalised threshold		Normalised threshold		Normalised threshold		Normalised threshold		Normalised threshold		Normalised threshold		Normalised threshold		Normalised threshold	
RS	0.16		-0.08		-0.11		-0.14		-0.15		-0.10		0.02		0.00	
VV	0.06		-0.05		-0.12		-0.11		-0.08		-0.07		0.16		0.00	
KB	0.07		0.08		-0.02		0.00		-0.11		0.08		0.08		0.00	
UD	0.07		0.00		-0.08		-0.01		-0.11		0.00		-0.03		0.00	
Mean	**0.09**		**-0.01**		**-0.08**		**-0.07**		**-0.11**		**-0.02**		**0.06**		**0.00**	
Std error	**0.05**		**0.07**		**0.04**		**0.07**		**0.03**		**0.08**		**0.08**		**0.00**	

The threshold values obtained from the psychometric functions are shown in Figure 3.3(A). The data obtained were normalised to remove the effect of differences in visual acuity scores between the subjects. The data for the individual and mean normalised thresholds are shown in Table 3.2(B). Figure 3.3(B) shows a plot of the mean normalised thresholds (threshold value at each separation – pre-cue isolated letter threshold value) plotted as a function of the letter separation. Since there was no significant difference between the no pre-cue and pre-cue isolated letter thresholds, the thresholds at each separation condition were normalised with the pre-cue isolated letter threshold. Threshold values greater than zero indicate threshold elevation. The threshold values for separations greater than zero and significantly different indicate contour interaction. Threshold values less than zero indicates threshold reduction. Threshold values for separations less than zero and significantly different indicate facilitation. Threshold reduction was noticed between 0.2 and 1.0 letter width separation. However, facilitation (threshold was significantly lower) was obtained only at 0.8 letter width separation. Conversely, threshold elevation and contour interaction was noticed only at the abutting condition.

Figure 3.3: (A) Low contrast recognition thresholds are plotted as a function of separation in letter widths. Each datum represents the low contrast recognition threshold for each separation averaged across all subjects. The mean recognition thresholds for the isolated pre-cue and isolated no pre-cue letters are also shown in the same graph. The error bars represents ±1 SE. (B) Normalised thresholds are plotted as a function of separation in letter widths. The histograms represent the recognition thresholds normalised against the pre-cue isolated letter threshold (threshold value at each separation – pre-cue isolated letter threshold value) averaged across all the subjects. The error bars represent ±1 SE.

A

B

In addition, the mean normalised recognition thresholds (threshold value at each separation condition – pre-cue isolated letter threshold) were compared between the high (80%) and the low (5.8%) contrast conditions (see Table 3.3). The data for the high contrast condition were obtained from the Chapter 2. The mean normalised threshold values plotted in the form of histograms for both the high and the low contrast levels are shown in Figure 3.4.

Table 3.3 and Figure 3.4 show threshold elevation at abutting, 0.2 and 0.4 letter width separations at the high contrast level and only at the abutting condition for the low contrast level. However, a significant increase in the threshold and therefore contour interaction was noticed only at the abutting condition for both the high and the low contrast letters. Further, the normalised thresholds were lower for the low contrast letters than the high contrast letters at all the letter separation conditions. A mixed factor ANOVA showed a significant main effect of the letter separation on recognition thresholds $F(5, 40) = 26.30$, $p < 0.01$. Paired wise comparison showed a significant difference between 0.2 and 0.6 letter separations. A significant difference was also seen between abutting and rest of the separation conditions except 0.2 letter width separation. No significant interaction effect was noticed between the inter-letter separation and the contrast levels $(5, 40) = 1.37$, $p > 0.05$.

Figure 3.4: Depicts normalised thresholds plotted as a function of separation in letter widths. The histograms represent the mean normalised recognition thresholds for both the high (dark blue) and the low (light blue) contrast SGRL stimuli. The error bars represent ±1 standard error (SE).

Table 3.3: Depicts the mean normalised high and low contrast recognition thresholds for all the separation conditions.

Separation	HC Normalised thresholds	Std error	LC Normalised thresholds	Std error
Abutting	0.18	0.04	0.09	0.05
0.2	0.10	0.07	-0.01	0.07
0.4	0.02	0.03	-0.08	0.04
0.6	-0.01	0.03	-0.07	0.07
0.8	-0.02	0.04	-0.11	0.03
1.0	0.00	0.03	-0.02	0.08

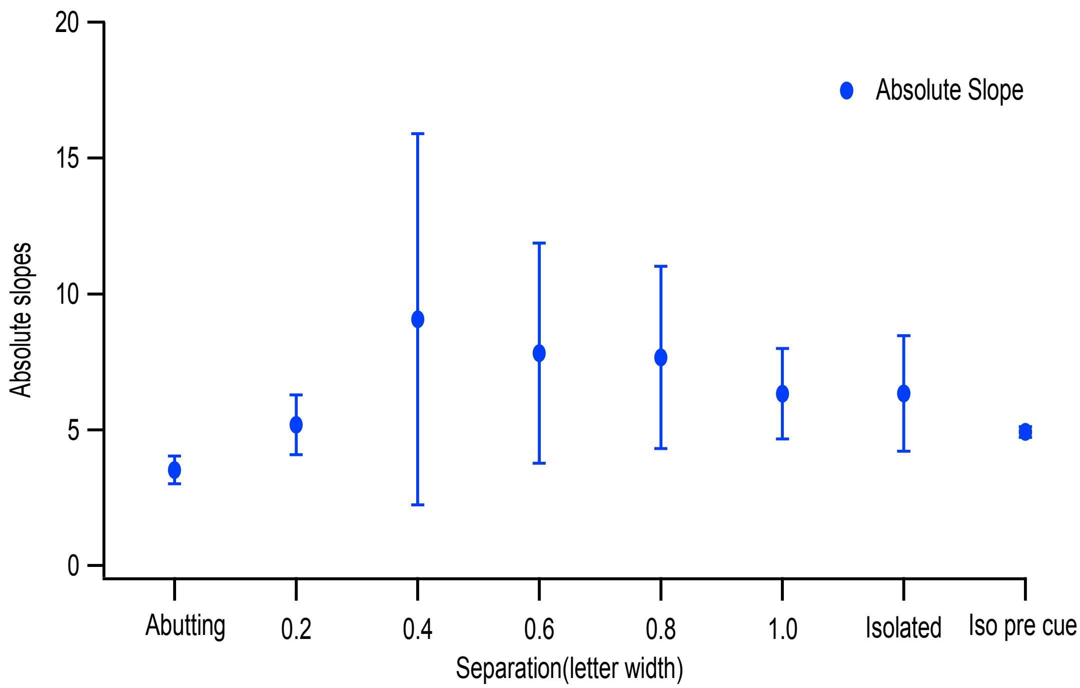
Slopes of psychometric functions

The slope values derived from the Weibull functions are shown in Table 3.4. Figure 3.5 shows the slope values plotted as a function of the letter separation. A smaller slope value at the abutting condition indicates a shallow curve and a corresponding increased difficulty in recognizing the letter in the array. It is apparent that the error bar at 0.4 letter width separation was wider than at other separation conditions. The reason for this is that subject (VV) had a larger slope value of 19.29 than the values obtained for the other subjects (see Table 3.4). The smaller error bars indicated nearly the same slope values between all the subjects at abutting and 0.2 letter width separations. The error bars for separations greater than 0.4 letter widths were wider than for the separations narrower than 0.4 letter widths. The 0.4 letter width separation appeared to be the boundary or transition zone between the separations where contour interaction was greatest (abutting condition) and the separations where there was no contour interaction effect (0.6, 0.8 and 1.0 letter width separation). Repeated measures within subjects one way ANOVA showed no significant effect of separation on slopes $F(1.38, 4.13) = 1.50$, $p > 0.05$. Any possible differences in slopes as a function of the letter width separation may be masked by the high variability of slope values at some separation distances.

Table 3.4: Depicts slopes obtained from the psychometric functions for each individual subject and the means of all subjects for each separation condition and pre-cue and no pre-cue isolated letter condition.

Separation	Abutting		0.2		0.4		0.6		0.8		1.0		Isolated	Isolated Pre Cue		
Subjects	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev
RS	3.05	0.56	4.02	0.39	5.15	0.93	5.20	0.78	5.13	0.66	4.18	0.65	5.01	0.23	4.98	0.78
VV	4.21	0.51	6.46	1.07	19.29	6.75	13.83	3.30	6.57	1.16	6.05	0.70	5.49	0.76	5.50	0.59
KB	3.25	0.41	5.70	0.16	6.17	1.18	6.60	1.28	12.60	2.93	6.86	1.10	9.50	0.31	4.80	0.56
UD	3.57	0.73	4.54	0.84	5.65	1.21	5.62	0.66	6.35	1.84	8.17	1.49	5.32	0.62	4.41	1.00
Mean	**3.52**		**5.18**		**9.06**		**7.82**		**7.66**		**6.32**		**6.33**		**4.92**	
Std error	**0.51**		**1.10**		**6.83**		**4.05**		**3.35**		**1.67**		**2.12**		**0.45**	

Figure 3.5: Average slope of the psychometric functions is plotted as a function of letter separation. Each datum represents the mean slope value averaged across all the subjects and for each of the separation condition. The error bars represent ±1 SE.



Discussion

The results of this experiment show that the effect of low contrast on contour interaction is variable among subjects. For two subjects the hardest condition for letter identification was at abutting. The isolated letter (no pre cue) threshold was the worst for another subject (VV). This unexpected finding may be explained by the difficulty experienced by this subject to detect and/or identify the isolated letter. This reasoning was strengthened by the result obtained with the isolated pre-cue condition. When the subject's (VV) attention was directed to the target location (isolated pre-cue) there was an improvement in the threshold visual acuity by approximately 0.16 LogMAR when compared to the no pre-cue isolated letter condition (Table 3.2A). When the isolated pre-cue letter was considered for comparison rather than the no pre-cue isolated letter condition, the highest threshold was obtained at abutting for the subject VV. This was similar to the result observed for other subjects. It is possible that the contrast sensitivity function (CSF) of this particular subject may be lower than that of the other subjects making identification of the letters harder. This could not be confirmed because the CSF of the subjects was not determined. No pathologies were observed that could indicate low CSF in this subject (VV). Previous studies showed that the recognition acuity was poor for the isolated low contrast than the isolated high contrast letters. This was assumed to be due to the requirement of detailed detection of the letter features for recognition of the isolated low contrast letters (Blommaert and Timmers, 1987; France and France, 1988; Sokol, Moskowitz, Reese, and Brown, 1990; Strasburger, Harvey and Rentschler, 1991). However, the pre-cue block aided to direct the subject's attention towards the isolated low contrast letter thereby reducing the search time and resulting in improved threshold visual acuity for the pre-cue than the no pre-cue isolated letter condition. Nevertheless, the mean pre-cue isolated letter visual acuity was poorer than the visual acuity thresholds for SGRL acuity of all the separation conditions except for the abutting (Table 3.2 and Figure 3.3 A).

Statistical analysis showed a significant effect of letter separation on low contrast recognition thresholds. A significant difference was found between the threshold at abutting and 0.8 letter width separation. Surprisingly, the 1.0 letter width separation was not significantly different from the abutting condition. The recognition threshold at each separation may be determined by both the effect of contour interaction and the ability to perceive the low contrast letters. At 0.8 letter width separation the effect of contour interaction may be negligible or non-existent. However, the neighbouring letters could act as facilitators in identifying the letter in a similar way that the pre-cue improved the isolated letter threshold. A similar finding of detection facilitation has been reported by other investigators when Gaussian blobs are separated by approximately 0.8 optotype distance (Hairol and Waugh, 2010). At 1.0 letter width the letters are widely separated, contour interaction is not present, but the flanking letters may be too far apart to provide any facilitation. It is conceivable that at inter-letter separations closer than 0.8 letter width the effect of contour interaction becomes more important and negates any advantages accruing from facilitation.

It is also evident from Table 3.3 that, at 1.0 letter separation, the normalised recognition thresholds for the high and low contrast letters were nearly 0.00

and -0.08 Log units respectively. Similarly, at the abutting condition, the normalised recognition thresholds for the high and low contrast letters were nearly 0.18 and 0.03 Log units respectively. Consequently, the normalised visual acuity scores was better for the low contrast than the high contrast letters by 0.08 Log units for 1.0 letter separation and 0.15 Log units at the abutting condition. This indicates that the visual thresholds are less influenced by the low contrast flanking letters (contour interaction is reduced) at both the extreme and intervening separation distances.

The present findings are similar to previous reports for normal subjects (Kothe and Regan, 1990a; Giaschi, Regan, Kraft and Kothe, 1993). However, in both of these previous studies Snellen type and isolated letter charts were used. Consequently the effect of contrast on crowding was confounded by contour interaction, gaze instability and attention factors. The present study is different to the previous studies (Kothe and Regan, 1990a; Giaschi, Regan, Kraft and Kothe, 1993) because the effect of contour interaction has been isolated from the detrimental effects of gaze inaccuracies and task complexity (attention) by using the repeat letter chart design.

Simmers, Gray, McGraw and Winn (1999a) investigated the effect of high (80%) and low contrast (6%) levels on contour interaction. They found a significant effect of separation for the high contrast letters but reported no contour interaction for the low contrast letters. Contour interaction was not investigated at the abutting condition. The apparent contrasting findings may be explained by the fact that Simmers, Gray, McGraw and Winn (1999a) employed the same size target for the high and low contrast conditions. However, the test distance was dependant on 75% isolated letter threshold for both the contrast levels. This distance will be shorter for the low contrast letters. Consequently, although the physical size of the letters used is the same, the angular subtense will be greater for the low contrast letters. Effectively, though the target flanker separations used is the same for the high and low contrast conditions, the flankers from the letters are more widely separated because of the greater angular subtends of the low contrast letters. This may reduce the effect of contour interaction and may be the reason why Simmers, Gray, McGraw and Winn (1999a) reported no contour interaction for the low contrast letters.

Strasburger, Harvey and Rentschler (1991) studied the effect of crowding at the fovea and in the periphery. Numeric characters of different sizes were arranged in the form of a trigram and at a range of inter optotype separations (abutting to 2.0). However, the method of determining the crowding effect was different to the present study. Strasburger, Harvey and Rentschler (1991) determined the contrast thresholds needed to identify the middle number in a trigram when the flankers (other numbers) were presented at separations ranging from abutting to 2.0 optotype widths. They found that the foveal contrast threshold needed to identify the middle number in the trigram was independent of the separations (i.e. a constant contrast was required to identify the middle number with flanking numbers at a range of separations) and for different optotype sizes. They concluded that contour interaction is absent at the fovea. On the contrary, in the peripheral retina, higher contrasts were needed to identify the middle number when the trigram had closer optotype separations. They concluded that contour interaction is affected by the contrast level in the periphery of retina.

Conclusion

In conclusion, contour interaction is demonstrable at the fovea for low contrast targets when flankers are abutting. However, the effect is less for low contrast than high contrast optotypes. The reason for this difference might be related to the difficulty in detecting the low contrast letters. Reduced detection might translate to diminished interaction between the letters and consequently reduced contour interaction. One possible implication of the above finding relates to the pathological conditions where the contrast sensitivity of the eye is reduced. Such cases might include amblyopia, cataract and optic nerve diseases. Low contrast letter charts have been used in various studies to detect visual loss in patients with diabetic retinopathy (Regan and Neima, 1984), to detect abnormal contrast sensitivity function in children (France and France, 1988), and to study the effect of glare on visual acuity (Regan, Giaschi and Fresco, 1993). Based on the above finding it would be predicted that contour interaction in these situations might be less (because of a lower CSF) than what is obtained for the control (normal) subjects. This may have important clinical implications in the diagnosis and management of such conditions. Also, the critical spacing for high contrast may not be applicable for low contrast, as for the same separation between high and low contrast, contour interaction was less for the low contrast condition. Consequently, the effect of contour interaction on high and low contrast letters in amblyopic subjects is studied in the next chapter.

Chapter 4

The effect of contour interaction on high and low contrast SG repeat letters in subjects with amblyopic vision

Introduction

In the 2nd and 3rd Chapters, the effect of contour interaction on high (80%) and low (5.8%) contrast letters was investigated in subjects with normal vision. The results showed a significant effect of the letter separation on visual acuity thresholds at both the contrast levels. The visual acuity thresholds were less for the low contrast than the high contrast letters for all the separation conditions. The present Chapter will focus on the effect of contour interaction for high and low contrast SGRLs but in amblyopic subjects.

Previous studies have investigated the effect of the high contrast on contour interaction in normal and amblyopic subjects (Flom, Weymouth and Kahneman, 1963; Jacobs, 1979; Hess and Jacobs, 1979; Simmers, Gray, McGraw and Winn, 1999a; Hess, Dakin, Tewfik and Brown, 2001). Previous studies have suggested that contour interaction scaled with visual acuity scores in normal and amblyopic vision (Flom, Weymouth and Kahneman, 1963; Levi, Klein and Aitsebaomo, 1985; Simmers, Gray, McGraw and Winn, 1999a). The scaling of contour interaction between the normal and amblyopic eyes may be due to the reduced effect of gaze instability and attention with the target type used in the studies where optotypes were surrounded by flanking bars (Flom, Weymouth and Kahneman, 1963; Levi, Klein and Aitsebaomo, 1985; Simmers, Gray, McGraw and Winn, 1999a).

On the other hand, other studies have suggested that crowding did not scale with visual acuity scores and was more in amblyopes than subjects with normal vision (Hess, Dakin, Tewfik and Brown, 2001; Levi, Hariharan and Klein, 2002; Bonneh, Sagi and Polat, 2004; Hariharan, Levi and Klein, 2005; Bonneh, Sagi and Polat, 2007; Chung, Li and Levi, 2008). The non-scaling of crowding between the normal and amblyopic eyes may be due to the involvement of gaze fixations and attention while resolving the gap in Illiterate E in a TEVA chart (see Bonneh, Sagi and Polat, 2004; 2007). A TEVA chart is similar to a clinical LogMAR chart but is constructed with E's arranged in different directions and subjects have to identify the direction of the central E. This reasoning is based on the previous studies that the amblyopes display greater gaze instability thereby resulting in more crowding than normal subjects (Ciuffreda, Levi and Selenow, 1991), thus resulting in the non-scaling of crowding between the normal and amblyopic eyes. However, Stuart and Burian (1962) showed that crowding scaled in normal and amblyopic subjects while their stimulus (7x7 array of E's) required imposed gaze fixations to resolve the direction of each E in the chart. This discrepancy in the results between the previous studies lead to a unclear information regarding the scaling of contour interaction or crowding in normal's and amblyopes.

Further, amblyopia is associated with reduced visual acuity (Noorden, 1985; Ciuffreda, Levi and Selenow, 1991; Simons, 2005) and reduced spatial contrast sensitivity (Levi and Harwerth, 1977; Hess and Howell, 1977; Bradley and

Freeman, 1981). As a result of the reduced spatial contrast sensitivity, the perceived contrast of a target with the amblyopic eye (AE) may be lower than in a non-amblyopic eye (NAE). The results of Chapters 2 and 3 showed that, in normal subjects, contour interaction was less for low contrast stimulus, similar to the findings of Simmers, Gray, McGraw and Winn (1999a). It follows that it would be important to study the effect of contrast on contour interaction in amblyopes especially due to their reduced visual acuity and contrast sensitivity. Therefore, this Chapter will investigate the effect of the high and low contrast SGRLs on contour interaction in amblyopic vision and compare results between the non-amblyopic and amblyopic eyes.

Methods

Apparatus & Stimuli

The stimuli were generated on a Dell computer using MATLAB (The Math Works, MA) software. The stimuli were displayed on a gamma corrected 17" Sony monitor (model number GDM-F520) using a CRS 2/5 graphics card. The luminance of the screen was 123 cd / m^2 when measured using an optical photometer. The screen resolution was 1024 x 769 with a frame rate of 120 hz. The stimuli were the seven SG letters presented either in isolated and SGRL chart format as described in the 2nd and 3rd Chapters of this thesis. The SGRL chart comprised a single SG letter repeated in a 7x7 array, totally 49 letters. In order to maintain equality of contour interaction for the outside repeated letters, each of the repeated 7x7 arrays was surrounded by an additional single letter array of randomly allocated SG letters. The separations used were 1.0, 0.6, 0.4, 0.2 times the test letter size and an abutting condition. Both the high

(80%) and the low contrast (12% - 20%) stimuli were generated using Matlab. A contrast level of less than 20% was maintained for the low contrast SG letters where visual acuity is expected to be influenced at such a low contrast (see Herse and Bedell, 1989). Each of the high and the low contrast letters had a stroke width of 3 pixels with a total letter diameter of 15 pixels. The low contrast level of the letters was determined by setting the contrast at 2 times the contrast threshold obtained using 11 contrast levels of the isolated letters. SGRL charts were presented at random in runs of 70 trials per separation condition, so that each individual SGRL array and separation condition was presented at least 10 times per run. Each subject was first presented with the high contrast stimuli. The low contrast stimuli were presented after the data collection for the high contrast was completed.

Procedure

General condition

Five naive amblyopic subjects aged between 20 and 27 participated in the study (see Table 4.1). All subjects had best corrected visual acuity of 6/6 or better in the non-amblyopic eye. For the purpose of this study, amblyopia was defined as a difference in visual acuity of one or more than one Snellen line between the amblyopic and the non-amblyopic eye. All subjects were fully corrected and wore their best optical correction. Informed consent was obtained from all the subjects after the nature and the consequences of the study were explained.

Table 4.1: Depicts the visual features of the amblyopic subjects.

Subjects	Gender	Age	Type	Eye	VA	Refractive error	Eye alignment	Stereo acuity	Fixation
PL	F	27	S+A	OD	6/7.5	-3.00	12Δ R ET	-	9.2mm@ 30 cm
				OS	6/6+1	-1.50/-0.25x170	0.5Δ L HyperT	-	-
AB	F	21	A	OD	6/4	+0.50/-0.25x110	-	-	-
				OS	6/5-2	+3.50/-0.50x70	-	240"	-
RC	F	21	A	OD	6/6+3	+1.75/-0.25x100	-	-	-
				OS	6/12	+4.50/-0.25x80	-	-	-
VS	F	21	A	OD	6/7.5-1	+1.25	1Δ R HypoT	120"	-
				OS	6/5+1	+0.75/-0.75x180	-	-	-
SR	F	20	S	OD	6/4-3	+4.75/-2.00x155	-	-	-
				OS	6/18+2	+4.00/-0.25x155	14Δ L ET	-	11.6mm@ 30 cm

Subjects viewed the monitor monocularly with either the amblyopic or non-amblyopic eye either directly or if required, through an optical quality front surface mirror and performed a single-interval 7-alternative forced choice task. Subjects were required to identify the repeated letter in the central 7x7 array. No restriction was placed on where the subjects fixated within the array to make their decision. A method of constant stimuli was used where the size of the letters was varied by varying the test distance according to a logarithmic scale. The order of the test distances (moving from closer to further or further to closer), eyes (non-amblyopic and amblyopic eye) and stimuli condition (SGRL and isolated letter) were randomised between the runs and for all the subjects. Testing distances varied from the guess rate to 100% correct responses in order to generate psychometric curves. The test distances varied between both the eyes depending on the visual acuity differences between the amblyopic and the non-amblyopic eyes. Unlike the procedure in Chapters 2 and 3, the viewing time was unlimited and the responses were obtained using a wireless keyboard but sometimes the responses were noted by the examiner. All subjects underwent a practice session before the main experiment to provide familiarity with the SGRL chart. Sufficient practice data were taken at the 1.0 letter separation condition to generate a psychometric function. Breaks were allowed in between the experimental runs to lessen fatigue. Each datum was the average of at least three runs of 70 trials.

Control condition

1. Recognition thresholds were measured for an isolated SG letter at both the high and the low contrast levels. The procedure and the subject's task were the

same as that of the main experiment described in the general condition. Threshold for the isolated SG letters was compared to the thresholds of the five separation conditions at both the contrast levels.

2. A second control experiment was conducted to make sure no differences in the results occurred due to the changes in the methodology followed when Microsoft PowerPoint™ and Matlab were used. One subject VV who participated while investigating the effect of contour interaction using SGRL chart designed in Microsoft PowerPoint™ was made to repeat the experiment when the stimuli were designed using Matlab. The control experiment was carried out before the main experiment was actually started. The procedure was the same as that described in the main experiment condition. Figure 4.1 represent the graph consisting of psychometric functions for each of the separation condition obtained with a SGRL stimuli designed in Matlab. Figure 4.2 show the comparison of the thresholds at each separation condition obtained using Microsoft PowerPoint™ and Matlab.

Figure 4.1: The graph shows psychometric curves (coloured lines) for subject VV with percentage correct recognition of SG letters at five separation conditions and the isolated letter condition plotted as a function of visual acuity. Each datum shown represents the average of at least 210 trials at each distance measured. Error bars represent ± 1SD.

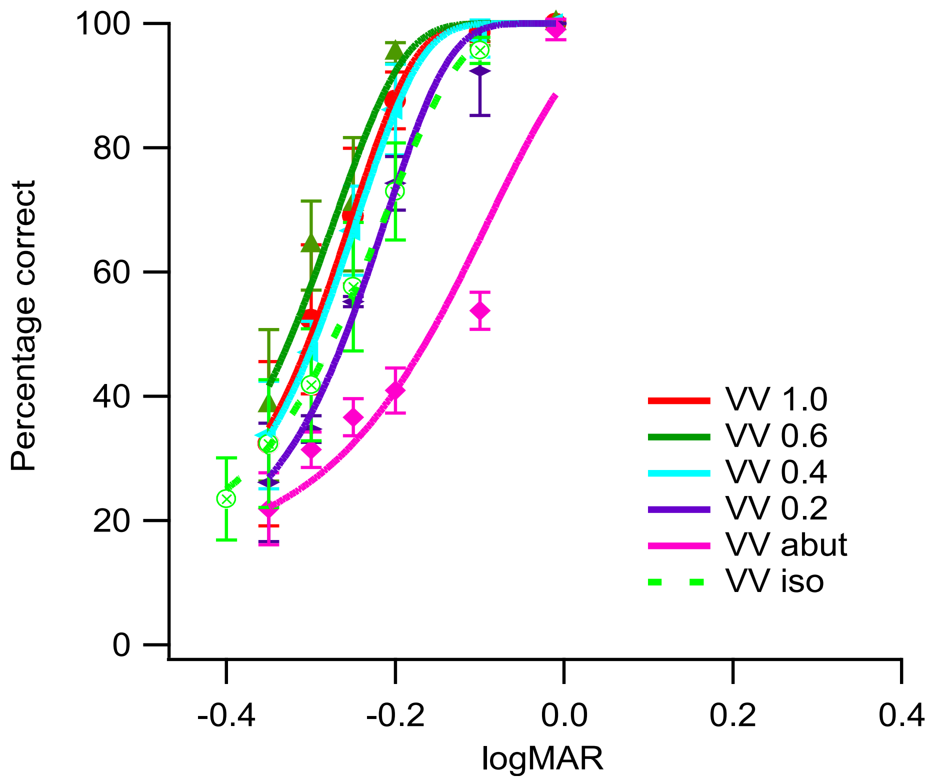
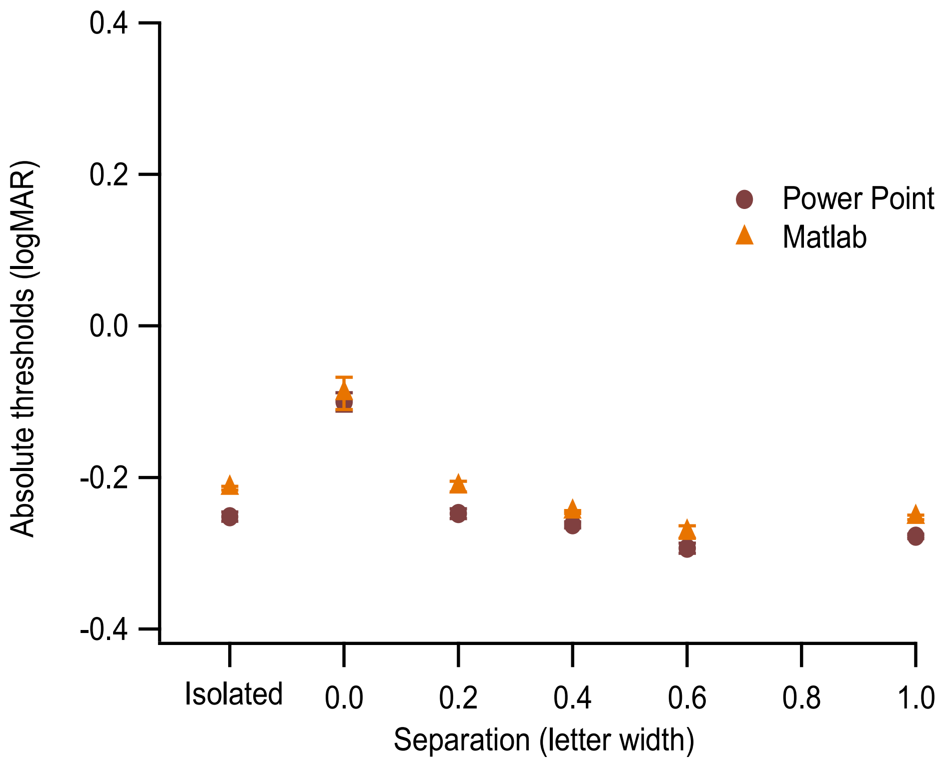


Figure 4.2: The recognition thresholds are plotted as a function of separation in letter widths. The graph shows the comparison of the SGRL thresholds obtained using Microsoft PowerPoint™ and Matlab programming. Each data point represents the recognition thresholds derived from the psychometric functions at each separation condition and isolated letter condition. The error bars represent ±1 SD.



The results indicated no significant differences in the methodology followed using Microsoft PowerPoint™ and Matlab ($p=0.27$; t-test).

3. A fixed low contrast stimulus may affect the precise visual acuity measurements due to the differences in the contrast sensitivity functions depending on the degree and type of amblyopia (Hess and Howell, 1977; Levi and Harwerth, 1977). The contrast thresholds were measured in order to choose a low contrast level to be presented to each amblyopic subject and be certain that the low contrast stimulus is visible to the non-amblyopic and amblyopic eyes. The testing distance was based on 2 times the threshold size obtained for the high contrast (80%) isolated SG letters. The details of conversion of the high contrast isolated letter thresholds in LogMAR units to the respective test distances to measure the contrast thresholds are shown in Table 4.2.

Table 4.2: Depicts the test distances corresponding to the high contrast isolated letter thresholds and twice the isolated letter threshold values for non-amblyopic and amblyopic eyes of each individual subject.

Subject	Eye	Isolated HC threshold in LogMAR	Distance (m) corresponding to LogMAR values
AB	NAE	-0.30	7.34
		2X LogMAR	3.67
	AE	-0.17	5.45
		2X LogMAR	2.72
RC	NAE	-0.20	5.92
		2X LogMAR	2.96
	AE	0.10	2.92
		2X LogMAR	1.46
VS	NAE	-0.23	6.26
		2X LogMAR	3.13
	AE	-0.10	4.63
		2X LogMAR	2.32
SR	NAE	-0.16	5.39
		2X LogMAR	2.69
	AE	-0.09	4.60
		2X LogMAR	2.30

The isolated SG letters with eleven different contrast levels (that resulted in responses ranging from the guess rate to 100 % correct responses) were presented to the non-amblyopic and the amblyopic eyes at the test distances corresponding to two times the high contrast isolated letter thresholds. Each stimulus contrast level was presented 21 times resulting in 231 trials for 11 contrast levels within each run. The order of the presentation of the stimuli and the test distance were randomised between the amblyopic and the non-amblyopic eyes and between subjects. Subjects indicated their responses using a wireless key board or responses were noted by the examiner. Data were fit with a linear Weibull function using the following equation.

$$F(c) = 1-(1-\gamma)*\exp(-c/t \wedge s)$$

Where γ is the probability of correct responses equal to 1/n (where n is the number of SG letters used, i.e. 7), c is the contrast of the letters presented, t is threshold and s is slope. The data points reported in Figure 4.3 represent the responses from the average of at least 4 runs. Threshold was based on 68% correct responses in identifying the isolated low contrast SG letters. To ensure that the letter contrast was not a limiting factor when measuring the effect of low contrast on contour interaction in amblyopic vision, the contrast of the letters was set at 2 times the contrast threshold value. Finally, the low contrast SGRL chart and low contrast isolated letter were presented at subjects twice the contrast threshold values as shown in Table 4.3.

Figure 4.3: The percentage correct responses are plotted as a function of contrast levels. The datum points represent the low contrast letter recognition responses at 11 different contrast levels and for each subject. The psychometric functions of the amblyopic and non-amblyopic eyes are represented in red and blue colour respectively. The error bars represent ±1 SD.

Table 4.3: Depicts the contrast thresholds and twice the contrast threshold values for the non-amblyopic and amblyopic eyes of each individual subject

Subject	Eye	Contrast threshold	2 X contrast threshold
AB	NAE	8.21	16.41
	AE	8.46	16.93
RC	NAE	9.44	18.89
	AE	9.95	19.91
VS	NAE	7.95	15.90
	AE	6.42	12.84
SR	NAE	10.33	20.65
	AE	8.50	17.01

Data analysis

The data analysis followed was same as that mentioned in Chapters 2 and 3. The data were fitted in the form of psychometric curves with Weibull function (Pelli, Robson and Wilkins, 1988) using Igor Pro Software. The thresholds and slopes obtained from the psychometric curves were analysed using SPSS. A repeated measures ANOVA and post-hoc analysis using the Bonferroni test were performed as appropriate.

Results

High contrast condition

The percentage correct responses were plotted as a function of visual acuity for all subjects. Each psychometric curve represented by a different colour corresponds to an individual letter separation used in the experiment ranging from 1.0, 0.6, 0.4, 0.2 letter width separations and abutting condition. The data for the control condition (isolated letter) are also shown in the same graph (Figure 4.4). There is a tendency for the functions to shift across to the right, reflecting the increased difficulty in the letter recognition with decreased letter separation (i.e. contour interaction). Both the non-amblyopic and amblyopic eyes showed a minimal effect on the extent of the shift in the psychometric curves from 1.0 to 0.4 letter width separation indicating a minimal effect of contour interaction. All subjects showed maximum deterioration in the performance at the abutting condition.

Figure 4.4: The data shown in the figure are a layout of representative results of psychometric curves for all the amblyopic subjects, at each condition. Each datum shown represents the average of at least 210 trials at each test distance measured. Error bars represent ± 1SD. Panel A&B represents psychometric functions at high contrast condition for the amblyopic and the non-amblyopic eyes respectively.

A (amblyopic eyes)　　B (non-amblyopic eyes)

Table 4.4(A) and 4.4(B): Depicts the recognition thresholds obtained for all the high contrast letter separations and high contrast isolated letter condition along with their mean thresholds for the non-amblyopic eyes and amblyopic eyes respectively.

NAE (A)												
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
AB	-0.12	0.01	-0.22	0.01	-0.27	0.01	-0.31	0.00	-0.35	0.00	-0.30	0.01
PL	0.00	0.01	-0.13	0.01	-0.20	0.01	-0.22	0.00	-0.24	0.00	-0.20	0.01
RC	0.06	0.01	-0.07	0.01	-0.14	0.02	-0.19	0.00	-0.21	0.00	-0.20	0.01
VS	-0.05	0.01	-0.17	0.01	-0.21	0.01	-0.33	0.01	-0.27	0.01	-0.23	0.01
SR	0.03	0.03	-0.08	0.01	-0.14	0.00	-0.20	0.00	-0.19	0.01	-0.16	0.02
Mean	**-0.02**		**-0.13**		**-0.19**		**-0.25**		**-0.25**		**-0.22**	
Std error	**0.07**		**0.06**		**0.05**		**0.07**		**0.06**		**0.05**	
AE (B)												
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
AB	-0.01	0.02	-0.16	0.01	-0.19	0.01	-0.22	0.01	-0.25	0.01	-0.17	0.01
PL	0.17	0.01	0.07	0.00	0.00	0.01	-0.02	0.00	-0.02	0.01	0.00	0.01
RC	0.34	0.03	0.16	0.01	0.11	0.01	0.08	0.01	0.06	0.01	0.10	0.00
VS	0.15	0.02	0.00	0.01	-0.06	0.00	-0.09	0.00	-0.09	0.00	-0.10	0.01
SR	0.28	0.02	0.11	0.01	0.05	0.01	-0.02	0.02	-0.03	0.02	-0.09	0.00
Mean	**0.19**		**0.04**		**-0.02**		**-0.05**		**-0.07**		**-0.05**	
Std error	**0.13**		**0.12**		**0.11**		**0.11**		**0.12**		**0.10**	

The change in threshold visual acuity as a function of separation for each individual amblyopic subject is shown in Figure 4.5. The non-amblyopic and amblyopic eyes showed similar patterns of change in the recognition thresholds for each of the separation condition and for all the subjects. The thresholds were higher for the amblyopic eyes than the non-amblyopic eyes at all the separation conditions measured. The difference between the non-amblyopic to amblyopic eye thresholds at all the separation conditions were nearly constant and were assumed to depend on the degree of amblyopia. The thresholds started to increase with decreased inter-letter separation. The maximum increase in the thresholds was at abutting condition. Also, the thresholds for the amblyopic and non-amblyopic eyes at each of the separation conditions scaled with the isolated letter threshold. The threshold values derived from the psychometric functions and their means for the non-amblyopic and amblyopic eyes are shown in Table 4.4.

Figure 4.5: Recognition thresholds are plotted as a function of separation in letter widths for each amblyopic subject. Each datum represents the high contrast recognition threshold for each separation condition. The datum points in blue and red represents the thresholds for the non-amblyopic eyes and amblyopic eyes respectively. The error bars represents ±1 standard deviation (SD).

Figure 4.6(A) shows mean recognition thresholds plotted as a function of the letter separation. The mean threshold values showed similar threshold patterns for both the amblyopic and non-amblyopic eyes and scaled with the isolated letter thresholds at each of the separation condition. The error bars were wider for the data points of amblyopic eyes. Repeated measures within subjects one way ANOVA for the non-amblyopic eyes showed a significant effect of letter separation on high contrast recognition thresholds $F (2.22, 8.88) = 102.79$, $p < 0.01$. Pair wise comparisons showed significant difference between the thresholds obtained for isolated letter (-0.22±0.05) to 0.2 letter separation (-0.13±0.06) and abutting condition (-0.02±0.07). A significant difference was also seen for 0.2 letter separation (-0.13±0.06) and abutting condition (-0.02±0.07) with rest of the separation conditions in the non-amblyopic eyes ($p < 0.05$). Further repeated measures within subjects one way ANOVA for the amblyopic eyes showed a significant effect of separation on high contrast recognition thresholds $F (1.27, 5.09) = 45.76$, $p < 0.01$. However, no significant difference was noticed between the thresholds obtained for the isolated letter (-0.05±0.10) to other separations in the amblyopic eyes ($p > 0.05$) except for abutting condition (0.19±0.14) where there was a marginal significant difference ($p=0.058$). The non statistical significant findings between the isolated letter thresholds and rest of the separations can be explained by the large error bars at each of the separation condition including the 1.0 letter width separation, implying a wider variation in the recognition thresholds of the amblyopic eyes. Pair wise comparison showed a significant difference in thresholds for 0.2 letter separation (0.04±0.12) and abutting condition (0.19±0.14) compared with rest of the separation conditions in amblyopic eyes.

The recognition threshold values of all the separations were normalised against the isolated letter condition (threshold value at each separation condition – isolated letter threshold value) and are shown in Table 4.5. Figure 4.6(B) shows the mean normalised threshold values as a function of letter separation. The mean normalised thresholds increased with decreasing inter-letter separation. The error bars were wider for the amblyopic eyes than the non-amblyopic eyes. The data points for the normalised threshold values for the amblyopic and the non-amblyopic eyes nearly overlaps each other at all the separations measured. This implies that contour interaction effect scales in the non-amblyopic and the amblyopic eyes when measured at the normalised recognition thresholds.

Figure 4.6: (A) Recognition thresholds are plotted as a function of separation in letter widths. Each datum represents the mean recognition threshold for each separation condition. The datum points in blue and red represents the mean thresholds for the non-amblyopic eyes and amblyopic eyes respectively. The error bars represents ±1 standard error (SE). (B) Recognition thresholds are plotted as a function of separation in letter widths. Each datum represents the mean recognition thresholds normalised against isolated letter threshold (threshold value at each separation - isolated letter threshold value). The datum points in blue and red represents the non-amblyopic eyes and amblyopic eyes respectively. The error bars represents ±1 standard error (SE).

A

B

Table 4.5(A) and 4.5(B): Depicts the normalised and the mean normalised thresholds for non-amblyopic and amblyopic eyes respectively, obtained at the high contrast level for all the letter separations.

NAE (A)						
Separation	Abutting	0.2	0.4	0.6	1.0	Isolated
Subjects	Normalized thresholds	Normalized thresholds	Normalized thresholds	Normalized thresholds	Normalized thresholds	Normalized thresholds
AB	0.18	0.08	0.03	-0.01	-0.05	0.00
PL	0.20	0.07	0.00	-0.02	-0.04	0.00
RC	0.27	0.13	0.06	0.02	-0.01	0.00
VS	0.18	0.06	0.01	-0.10	-0.05	0.00
SR	0.19	0.08	0.03	-0.03	-0.02	0.00
Mean	**0.20**	**0.08**	**0.03**	**-0.03**	**-0.03**	**0.00**
Std error	**0.04**	**0.03**	**0.02**	**0.04**	**0.02**	**0.00**
AE (B)						
Separation	Abutting	0.2	0.4	0.6	1.0	Isolated
Subjects	Normalized thresholds	Normalized thresholds	Normalized thresholds	Normalized thresholds	Normalized thresholds	Normalized thresholds
AB	0.15	0.01	-0.03	-0.05	-0.09	0.00
PL	0.17	0.06	-0.01	-0.02	-0.02	0.00
RC	0.23	0.06	0.00	-0.03	-0.05	0.00
VS	0.25	0.09	0.04	0.01	0.00	0.00
SR	0.38	0.20	0.14	0.07	0.06	0.00
Mean	**0.24**	**0.08**	**0.03**	**0.00**	**-0.02**	**0.00**
Std error	**0.09**	**0.07**	**0.07**	**0.05**	**0.06**	**0.00**

Figure 4.7 shows the normalised thresholds at the high contrast levels for the non-amblyopic and the amblyopic eyes same as the data shown in Figure 4.6(B) but plotted in the form of histograms. Threshold values greater than zero indicate threshold elevation. The threshold values for separations greater than zero and significantly different indicate contour interaction. Threshold values less than zero indicates threshold reduction. Threshold values for separations less than zero and significantly different indicate facilitation. There was a threshold elevation for abutting, 0.2 and 0.4 letter width separations and for non-amblyopic and amblyopic eyes. However, in non-amblyopic and amblyopic eyes, the thresholds at 0.2 letter separations and abutting were significantly different to rest of the letter separations indicating that the extent of contour interaction was at 0.2 letter width separation and the maximum intensity was at the abutting condition. The thresholds for 0.6 and 1.0 letter separation were significantly different to the rest of the separation conditions indicating facilitation at 0.6 and 1.0 letter separation in non-amblyopic and amblyopic eyes. The results indicated that the contour interaction effect scaled between the non-amblyopic and amblyopic eyes. Further, a two factor within subject factorial ANOVA was done for the separation and eyes (non-amblyopic and amblyopic). There was a significant effect of eyes on recognition thresholds $F (1, 4) = 42.18$, $p < 0.05$ and a significant effect of separation on recognition thresholds $F (1.732, 6.93) = 122.68$, $p < 0.01$. In addition, no significant interaction effect was noticed between the separation and eyes on the recognition thresholds $F (1.55, 6.21) = 0.68$, $p > 0.05$.

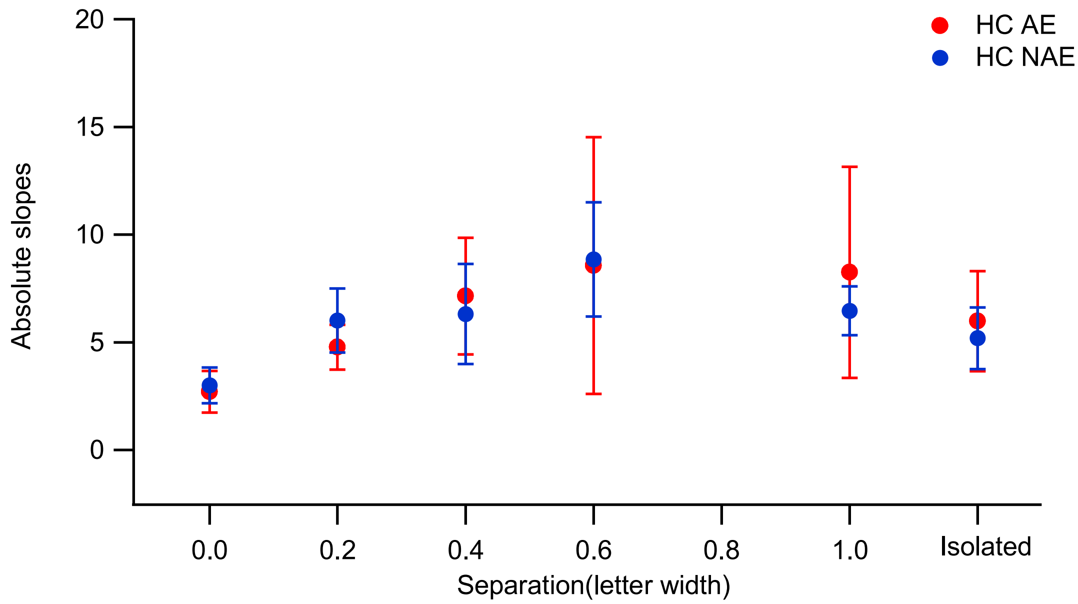
Figure 4.7: Depicts normalised thresholds plotted as a function of the letter separation. The histograms in blue and red represent the normalised thresholds for the non-amblyopic and amblyopic eyes respectively. The error bars indicate ± 1 SE.

Further, the estimates of slopes obtained from the psychometric curve fitting for each separation condition were analysed. The slope values are shown in Table 4.6. Figure 4.8 shows the mean slopes derived from the Weibull functions plotted as a function of letter separation. The slopes started to decrease with decreasing inter-letter separation in amblyopic eyes and slightly variable in the non-amblyopic eyes. Repeated measures within subjects one way ANOVA in non-amblyopic eyes at high contrast showed a significant effect of separation on slopes $F(1.88, 7.50) = 5.30$, $p < 0.05$. Pair wise comparisons showed a significant difference between abutting condition (2.99±0.84), 0.2 (6.01±1.49) and 0.6 (8.85±2.65) separation conditions. Further, repeated measures within subjects one way ANOVA in amblyopic eyes at high contrast showed no significant effect of separation on slopes $F(1.59, 6.36) = 3.50$, $p > 0.05$. This could be because of the large error bars for data points of amblyopic eyes at 1.0, 0.6 and 0.4 letter separations. This large variation in slopes between the amblyopic eyes could be due to the higher slope values for subject PL at 0.6 (19.01±4.10) and 1.0 (16.16±5.08) letter separation (see Table 4.6 B).

Table 4.6(A) and 4.6(B): Depicts the slopes and the mean slopes obtained at high contrast for all the separations and isolated letter condition for the non-amblyopic and the amblyopic eyes respectively.

NAE (A)												
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev
AB	1.89	0.15	4.60	0.55	5.46	0.56	6.79	0.23	7.27	0.72	5.24	0.64
PL	2.80	0.23	5.17	0.66	5.66	0.52	5.88	0.40	7.50	0.45	7.55	0.83
RC	2.66	0.19	5.17	0.74	10.07	5.24	8.50	0.94	6.89	0.52	4.61	0.32
VS	3.54	0.51	8.12	1.33	3.81	0.48	11.02	4.35	4.73	0.63	4.87	0.35
SR	4.08	1.46	6.99	1.45	6.51	0.92	12.04	1.99	5.92	1.10	3.70	0.81
Mean	**2.99**		**6.01**		**6.30**		**8.85**		**6.46**		**5.20**	
Std error	**0.84**		**1.49**		**2.32**		**2.65**		**1.14**		**1.43**	
AE (B)												
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev
AB	2.01	0.21	5.49	0.61	10.39	2.07	7.38	1.14	6.28	0.71	4.62	0.53
PL	4.07	0.56	4.47	0.12	8.73	2.31	19.01	4.10	16.16	5.08	9.94	2.23
RC	1.77	0.27	5.55	0.82	6.64	1.09	6.51	1.29	5.51	0.74	4.06	0.24
VS	3.32	0.78	5.26	0.53	6.81	0.33	5.86	0.53	9.56	0.75	6.00	1.19
SR	2.33	0.36	3.08	0.28	3.12	0.32	4.02	0.95	3.75	0.87	5.26	0.48
Mean	**2.70**		**4.77**		**7.14**		**8.56**		**8.25**		**5.98**	
Std error	**0.97**		**1.04**		**2.72**		**5.97**		**4.90**		**2.33**	

Figure 4.8: Depicts slopes plotted as a function of separation in letter widths. Each datum point in blue and red represents the mean slopes averaged across all the non-amblyopic and amblyopic eyes respectively. The error bars represents ±1 standard error (SE).



Low contrast condition

For all the four subjects (subject PL dropped out after the high contrast experiment) that participated in the study, the results were analysed and the graphs were plotted in the same way as for the high contrast data of the amblyopic subjects. The percentages of correct responses were plotted as a function of visual acuity (see Figure 4.9). The effect of contour interaction in the form of a shift in the psychometric curves was considered at each separation condition. All the subjects showed maximum deterioration in the performance at abutting condition for both the non-amblyopic and amblyopic eyes. The effect of contour interaction can be precisely obtained by comparing the thresholds obtained from the psychometric curves with the letter separation conditions. The low contrast recognition thresholds are shown in Table 4.7.

Figure 4.9: The data shown in the figure are a layout of representative results of psychometric curves for all the amblyopic subjects, at each separation condition and isolated letter condition. Each datum shown represents the average of at least 210 trials at each test distance measured. Error bars represent ± 1SD. Panel A&B represents psychometric functions at low contrast condition for the non-amblyopic and the amblyopic eyes respectively.

A (non-amblyopic eyes) B (amblyopic eyes)

Table 4.7(A) and 4.7(B): Depicts the thresholds and their means obtained at the low contrast for all the separations and isolated letter condition for the non-amblyopic and the amblyopic eyes respectively.

NAE (A)												
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
AB	0.17	0.02	0.02	0.01	-0.04	0.01	-0.05	0.02	-0.04	0.02	-0.03	0.01
RC	0.17	0.02	0.02	0.01	-0.02	0.01	-0.06	0.00	-0.08	0.01	-0.02	0.00
VS	0.15	0.01	-0.03	0.01	0.01	0.04	-0.12	0.02	0.00	0.03	-0.01	0.01
SR	0.24	0.03	0.10	0.00	0.02	0.00	-0.01	0.01	-0.01	0.00	0.01	0.02
Mean	**0.18**		**0.03**		**-0.01**		**-0.06**		**-0.03**		**-0.01**	
Std error	**0.04**		**0.05**		**0.03**		**0.05**		**0.04**		**0.02**	
AE (B)												
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
AB	0.15	0.01	0.02	0.01	-0.02	0.01	-0.04	0.01	-0.02	0.01	0.12	0.01
RC	0.38	0.01	0.22	0.00	0.17	0.01	0.15	0.01	0.16	0.01	0.22	0.01
VS	0.33	0.01	0.11	0.02	0.05	0.01	0.04	0.01	0.06	0.00	0.10	0.01
SR	0.31	0.01	0.12	0.02	0.06	0.01	0.02	0.01	0.01	0.01	0.05	0.00
Mean	**0.29**		**0.12**		**0.07**		**0.04**		**0.05**		**0.12**	
Std error	**0.10**		**0.08**		**0.08**		**0.08**		**0.08**		**0.07**	

Figure 4.10 shows a layout of individual subject's absolute thresholds (in LogMAR) plotted as a function of the letter separation. The data for subjects RC and VS showed a difference in the thresholds between the non-amblyopic and amblyopic eyes at all the separation conditions, while the data for subjects AB and SR showed not much difference in the thresholds between both the eyes and at all the separation conditions. Therefore, because of these differences in the results between the amblyopic subjects, the data for the low contrast letters were analysed in three different conditions. The mean absolute thresholds and the mean normalised thresholds were plotted for all the four subjects, only for the three anisometropic subjects (AB, RC, VS) separating the strabismic subject (SR) and only considering the two anisometropic subjects (RC, VS) separating subject (AB) who is a mild anisometropic amblyope. These comparisons are shown in the Appendices 2&3 at the end of this Chapter. Repeated measures within subjects one way ANOVA showed a significant effect of separation on low contrast recognition thresholds in all the three conditions and both the eyes tested. This indicates that there was no change in the overall significant effect in all the three different conditions irrespective of the differences in the individual subjects. For non-amblyopic eyes, the data for all the four subjects showed $F(1.36, 4.08) = 35.59$, $p < 0.05$, the data for the three subjects showed $F(1.25, 2.50) = 21.70$, $p < 0.05$ and the data for the two subjects showed $F(5, 5) = 10.09$, $p < 0.05$. For amblyopic eyes, the data for all the four subjects showed $F(1.25, 3.76) = 27.59$, $p < 0.05$, the data for the three subjects showed $F(1.19, 2.38) = 20.19$, $p < 0.05$ and the data for the two subjects showed $F(5, 5) = 41.75$, $p < 0.05$. Therefore, the average results of all the four subjects was considered and discussed in the main chapter.

Figure 4.10: Depicts the layout of each subject's data with recognition thresholds plotted as a function of separation in letter width. Each datum represents the low contrast recognition threshold for each separation condition. The datum points in blue and red represents the thresholds for the non-amblyopic eyes and amblyopic eyes respectively. The error bars represents ±1 SD.

Figure 4.11(A) shows mean absolute thresholds of all the four subjects plotted as a function of the letter separation. The low contrast recognition thresholds were higher for the amblyopic eyes than the non-amblyopic eyes. The error bars were larger for the data points of the amblyopic eyes than the non-amblyopic eyes. The mean low contrast thresholds decreased from 1.0 to 0.6 letter separations and later increased from 0.6 letter separation to abutting condition in both the non-amblyopic and amblyopic eyes. Such a decrease in the low contrast thresholds from 1.0 to 0.6 letter separation was also seen in subjects with normal vision and was described in Chapter 3. The maximum increase in the thresholds for the non-amblyopic and amblyopic eyes was at the abutting condition.

Repeated measures within subjects one way ANOVA showed a significant effect of separation on low contrast recognition thresholds in the non-amblyopic eyes $F(1.36, 4.08) = 35.59$, $p < 0.05$. Pair wise comparisons showed a significant difference between the thresholds obtained for the isolated letter condition (-0.01 ± 0.02) and abutting condition (0.18 ± 0.04). A significant difference was noticed between the thresholds obtained for abutting (0.18 ± 0.04) to rest of the separations and between 0.2 (0.03 ± 0.05) and 0.6 (-0.06 ± 0.05) letter width separations. Further, repeated measures within subjects one way ANOVA showed a significant effect of separation on the low contrast recognition thresholds in the amblyopic eyes $F(1.25, 3.76) = 27.59$, $p < 0.05$. Pair wise comparisons showed no significant difference between the isolated letter threshold and rest of the separation conditions. However, a significant difference was noticed between the thresholds obtained for abutting

(0.29±0.10) and 0.2 (0.12±0.08) to 0.4 (0.06±0.08) and 0.6 (0.04±0.08) separation conditions.

Figure 4.11: (A) Recognition thresholds plotted as a function of separation in letter widths. Each datum represents the mean low contrast recognition threshold for each separation condition. The datum points in blue and red represents the mean thresholds for the non-amblyopic eyes and amblyopic eyes respectively. The error bars represents ±1 SE. (B) Normalised recognition thresholds plotted as a function of separation in letter widths. Each datum represents the mean low contrast recognition thresholds normalised against the isolated letter threshold (threshold value at each separation - isolated letter threshold value). The datum points in blue and red represents the non-amblyopic eyes and amblyopic eyes respectively. The error bars represents ±1 SE.

A

B

The threshold values of all the separations were normalised against the isolated letter condition (threshold value at each separation - isolated letter threshold value) and are shown in Figure 4.11(B). The normalised low contrast threshold values are shown in Table 4.8. For all the letter separations tested, the normalised threshold values were lower for the amblyopic eyes than the non-amblyopic eyes. This indicated that in the low contrast condition, the amblyopic eyes seem less affected by the contour interaction effect than the fellow non-amblyopic eyes though not shown statistically. This could be due to the fact that, amblyopic eyes are already practiced or experienced with poor or blur vision and are therefore believed to be less sensitive to the low contrast condition, resulting in lower recognition thresholds in the amblyopic than the fellow non-amblyopic eyes. In addition, while it is known from Chapter 3 that contour interaction decreases with the low contrast letters, the perceived contrast of the low contrast letters may be less than the stimuli contrast presented to the amblyopic eyes resulting in lesser contour interaction effect in the amblyopic than the non-amblyopic eyes.

Further, the normalised thresholds at the low contrast levels for the non-amblyopic and the amblyopic eyes are plotted in the form of histograms (Figure 4.12). The results showed threshold elevation for abutting, 0.2 and 0.4 letter width separations for the non-amblyopic and for abutting and 0.2 letter width separation in the amblyopic eyes. However, in non-amblyopic eyes, the thresholds at abutting are significantly different to rest of the letter separations including the isolated letter thresholds and the thresholds at 0.2 letter width separation is significantly different to 0.6 letter width separation. On the other hand, in the amblyopic eyes, the thresholds at 0.2 letter width separations and abutting were significantly different to 0.4 and 0.6 letter width separation. This indicated that the extent of contour interaction was at 0.2 letter width separations and the maximum intensity was at the abutting condition for the non-amblyopic and amblyopic eyes. Further, a two factor within subject factorial ANOVA was done for separation and eyes (non-amblyopic and amblyopic). There was no significant effect of eyes on recognition thresholds $F(1, 3) = 5.14$, $p > 0.05$. There was a significant effect of separation on recognition thresholds $F(1.89, 5.68) = 56.24$, $p < 0.01$. There was no significant interaction effect between separation and eyes on recognition thresholds $F(1.68, 5.03) = 1.01$, $p > 0.05$.

Figure 4.12: Depicts normalised thresholds plotted as a function of letter separation. The histograms in blue and red represent the mean normalised thresholds for non-amblyopic and amblyopic eyes respectively. The error bars indicate ± 1SE.

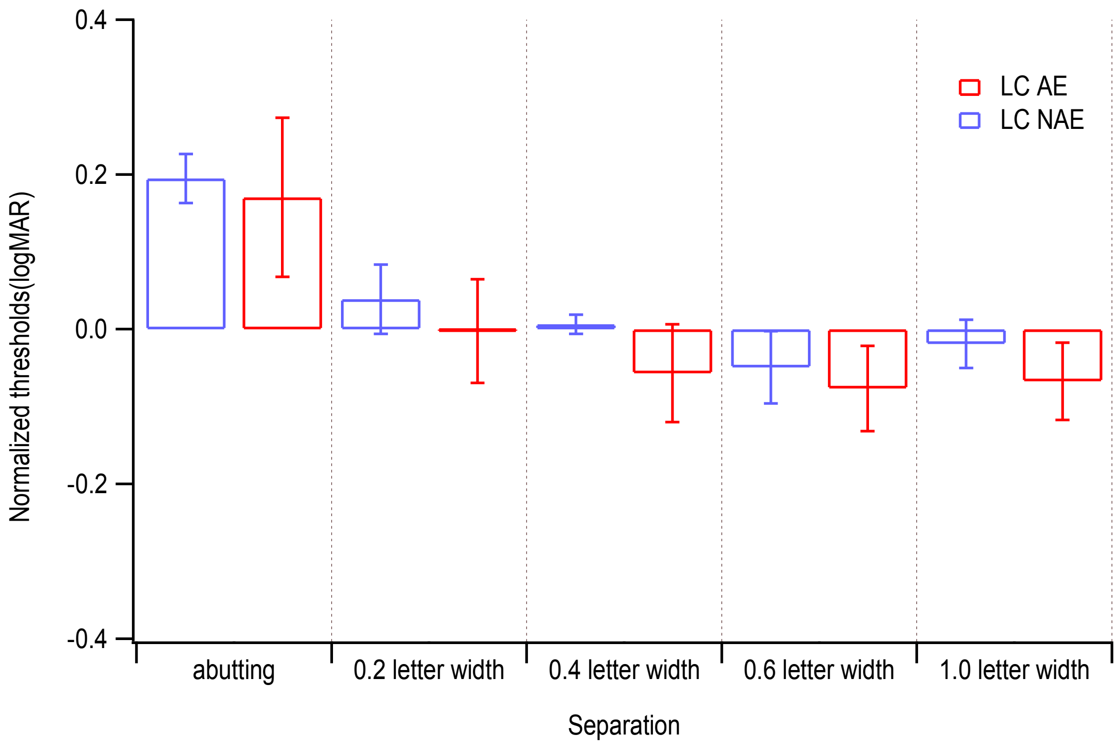


Table 4.8(A) and 4.8(B): Depicts the normalised and the mean normalised thresholds obtained at the low contrast level for all the separations and the isolated letter condition and for the non-amblyopic and amblyopic eyes respectively.

NAE (A)						
Separation	Abutting	0.2	0.4	0.6	1.0	Isolated
Subjects	Normalized	Normalized	Normalized	Normalized	Normalized	Normalized
	thresholds	thresholds	thresholds	thresholds	thresholds	thresholds
AB	0.20	0.05	0.00	-0.02	0.00	0.00
RC	0.19	0.04	-0.01	-0.05	-0.06	0.00
VS	0.16	-0.02	0.02	-0.12	0.01	0.00
SR	0.23	0.09	0.01	-0.02	-0.02	0.00
Mean	**0.20**	**0.04**	**0.01**	**-0.05**	**-0.02**	**0.00**
Std error	**0.03**	**0.05**	**0.01**	**0.05**	**0.03**	**0.00**
AE (B)						
Separation	Abutting	0.2	0.4	0.6	1.0	Isolated
Subjects	Normalized	Normalized	Normalized	Normalized	Normalized	Normalized
	thresholds	thresholds	thresholds	thresholds	thresholds	thresholds
AB	0.03	-0.09	-0.14	-0.15	-0.14	0.00
RC	0.16	0.00	-0.04	-0.06	-0.06	0.00
VS	0.23	0.01	-0.06	-0.06	-0.04	0.00
SR	0.26	0.07	0.01	-0.02	-0.03	0.00
Mean	**0.17**	**0.00**	**-0.06**	**-0.07**	**-0.07**	**0.00**
Std error	**0.10**	**0.07**	**0.06**	**0.06**	**0.05**	**0.00**

Further, the estimates of slopes for each separation condition were analysed. The slope values are shown in Table 4.9. Figure 4.13 shows mean slopes plotted as a function of the letter separation. Repeated measures within subjects one way ANOVA showed no significant effect of separation on slopes at low contrast level in the non-amblyopic eyes $F(2.46, 7.39) = 1.84$, $p > 0.05$. Further, repeated measures within subjects one way ANOVA showed no significant effect of the separation on slopes at low contrast level in the amblyopic eyes $F(2.24, 6.72) = 2.24$, $p > 0.05$.

Figure 4.13: Depicts the slopes plotted as a function of the letter separation. Each datum point in blue and red represents the mean slopes averaged across all the non-amblyopic and amblyopic eyes respectively. The error bars represents ±1 SE.

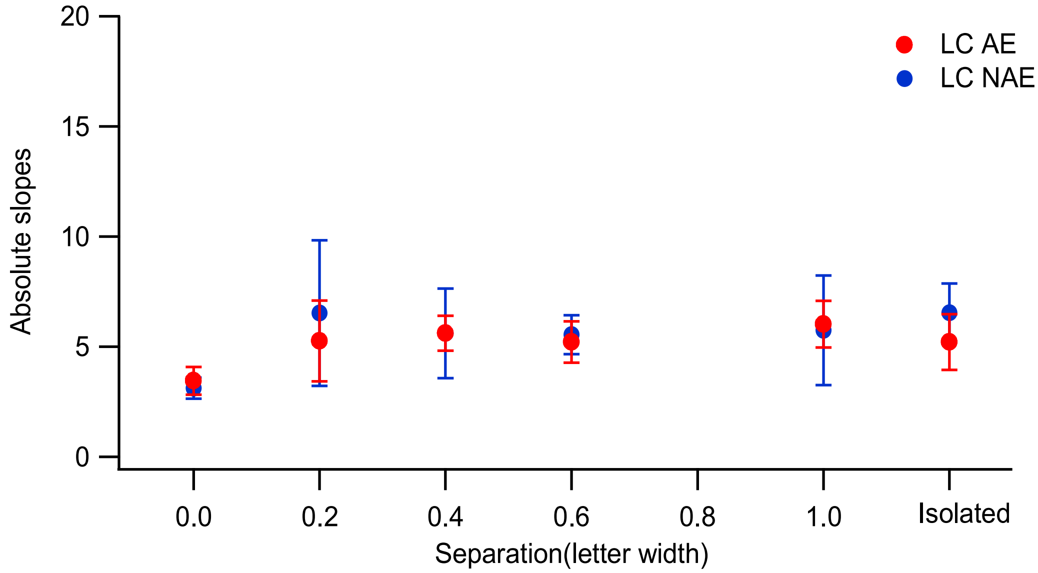


Table 4.9(A) and 4.9(B): Depicts the slopes and the mean slopes obtained at the low contrast level for all the separations and the isolated letter condition and for the non-amblyopic and amblyopic eyes respectively.

NAE (A)												
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Slopes	Std dev	Slopes	Std dev	Slopes	Std dev	Slopes	Std dev	Slopes	Std dev	Slopes	Std dev
AB	2.85	0.62	4.60	0.41	7.11	0.90	5.35	1.22	4.54	0.97	7.13	1.40
RC	3.73	0.62	11.42	2.55	6.84	2.22	4.64	0.46	7.82	1.83	7.64	0.33
VS	3.26	0.35	5.74	0.54	2.69	0.75	5.46	1.66	2.81	0.48	6.76	1.94
SR	2.65	0.62	4.38	0.10	5.83	0.24	6.77	1.73	7.81	0.46	4.61	1.02
Mean	**3.12**		**6.54**		**5.62**		**5.56**		**5.75**		**6.54**	
Std error	**0.48**		**3.31**		**2.03**		**0.89**		**2.49**		**1.33**	
AE (B)												
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Slopes	Std dev	Slopes	Std dev	Slopes	Std dev	Slopes	Std dev	Slopes	Std dev	Slopes	Std dev
AB	4.20	0.32	5.34	0.52	6.23	1.31	5.89	1.06	4.73	0.76	3.33	0.42
RC	2.66	0.28	7.84	0.70	5.20	0.51	4.94	0.97	6.15	0.74	5.76	0.65
VS	3.46	0.19	3.90	0.69	4.71	0.37	4.03	0.59	5.93	0.22	5.73	0.89
SR	3.52	0.48	3.98	0.85	6.33	1.22	6.00	1.10	7.30	1.13	6.06	0.53
Mean	**3.46**		**5.27**		**5.62**		**5.22**		**6.03**		**5.22**	
Std error	**0.63**		**1.84**		**0.79**		**0.92**		**1.05**		**1.27**	

High and low contrast condition

The normalised thresholds were compared between the high and the low contrast letters and for the non-amblyopic and amblyopic eyes (see Figure 4.14). For both the non-amblyopic and amblyopic eyes, the normalised thresholds were higher for the high contrast than the low contrast at all the separation conditions except for the non-amblyopic eyes at 1.0 letter separation.

Figure 4.14(A) & 4.14(B): Depicts the effect of contrast on contour interaction in non-amblyopic and amblyopic eyes respectively. The mean normalised thresholds are plotted in the form of histograms. The histograms in blue and red represent the normalised thresholds for non-amblyopic and amblyopic eyes respectively. The error bars indicate ± 1 standard error.

Discussion

The current experiment investigated the effect of contour interaction on high and low contrast repeat letters in amblyopic and non-amblyopic eyes. The results suggested a significant effect of separation on the high and low contrast recognition thresholds for the non-amblyopic and amblyopic eyes. No significant effect of separation on slopes was noticed in the non-amblyopic and amblyopic eyes at low contrast level and in the amblyopic eyes at the high contrast level. However, there was a significant effect of separation on slopes in the non-amblyopic eyes at the high contrast levels. Further, the spatial extent of contour interaction was at 0.2 letter width separation and the maximum intensity was at the abutting condition for both the eyes (non-amblyopic and amblyopic) and contrast levels (high and low contrast). The results also indicated that the magnitude of contour interaction scaled with the isolated visual acuity scores in the non-amblyopic and the amblyopic eyes when the interaction effect was measured at the subjects' recognition thresholds. Further, the maximum increase in the thresholds at abutting condition could possibly be due to the lack of the detailed detection of letter features at closer separation resulting in an increased response bias and increased contour interaction at closest target flanker separation. In addition, in a low contrast condition, the thresholds were less for the amblyopic eyes than the non-amblyopic eyes. This indicates that the amblyopic eyes are less affected by the contour interaction at the low contrast level than the fellow non-amblyopic eyes (see Figure 4.11B). Also, though the extent of contour interaction was at 0.2 letter width separation for the high and low contrast letters, the normalised thresholds were less for the low contrast than the high contrast for both the non-amblyopic and amblyopic eyes (see Figure 4.14). Further, the effect of contour interaction was similar in strabismic (SR) and anisometropic amblyopes (PL, AB, RC, VS) at high contrast level (see Figure 4.5). However, this was not the same at the low contrast level. The low contrast recognition thresholds were higher for the amblyopic eyes than the non-amblyopic eyes in anisometropic amblyopes (RC and VS) while the low contrast recognition thresholds were nearly the same at all the separation conditions between the non-amblyopic and amblyopic eye of the strabismic amblyope (SR) (see Figure 4.10).

The results of the present study are in agreement to the results reported in the previous studies that showed that contour interaction effect scales in the normal and amblyopic eyes when visual acuity was measured at the individual's visual thresholds (Stuart and Burian, 1962; Flom, Weymouth and Kahneman, 1963; Levi, Klein and Aitsebaomo, 1985; Simmers, Gray, McGraw and Winn, 1999a).

Flom, Weymouth and Kahneman (1963) showed that resolution was impaired as the separation between a Landolt C and surrounding flanking bars decreased to 4.7 multiples of gap widths in normal eyes and 6.8 multiples of gap widths in the amblyopic eyes. They found that the magnitude of contour interaction was similar in normal and amblyopic eyes when contour interaction was plotted in multiple of gap widths. They concluded that the magnitude of contour interaction scaled in normal and amblyopic eyes when measured at the resolving capacity of the eye. The results of the present study are also consistent with the results of Simmers, Gray, McGraw and Winn (1999a) who found scaling of contour interaction effect between normal and amblyopic eyes in agreement with Flom, Weymouth and Kahneman (1963) results. Though less relevant to the present study, similar results were obtained by Levi, Klein and Aitsebaomo (1985) who showed that the extent of interaction using a vernier acuity task was proportional to the isolated vernier threshold in normal and amblyopes and stated that the extent of interaction with the vernier acuity task scaled with the isolated vernier acuity. Though Flom's (Flom, Weymouth and Kahneman, 1963) experiment involved a resolution task while Simmers (Simmers, Gray, McGraw and Winn, 1999a) experiment involved a recognition task and Levi's (Levi, Klein and Aitsebaomo, 1985) experiment involved a vernier task, all the three studies and the current study showed similar results. This implies that the scaling of the contour interaction effect is assumed to be independent of the type of the task involved. Also, though the previous studies had flanking bars as distractors and the present study had letters as distractors, all the studies showed similar results. This implies that the scaling of contour interaction effect is independent of the flanker type in non-amblyopic and amblyopic eyes.

Other studies showed that the contour interaction in the amblyopic fovea is scale invariant and occurs at a greater distance in amblyopic than normal eyes (Hess and Jacobs, 1979; Hess, Dakin, Tewfik and Brown, 2001; Levi, Klein and Hariharan, 2002; Hariharan, Levi and Klein, 2005; Bonneh, Sagi and Polat, 2004; 2007; Chung, Li and Levi, 2008). For example, Levi, Klein and Hariharan (2002) and Hariharan, Levi and Klein (2005) investigated foveal contour interaction in normal and amblyopic vision by measuring the contrast thresholds needed to resolve the direction of an isolated and flanked E or C patterns made of Gaussian and Gabor patches. They found that in normals, contour interaction depends on the target size and the increase in thresholds while resolving the flanked target was due to the contrast masking from the adjacent flankers. In amblyopes however, contour interaction did not depend on the target size and the extent of crowding was greater in amblyopes was not due to contrast masking but was thought to result from pooling of the target and the flankers. However, the difference between the results of the present study and the results of Levi, Klein and Hariharan (2002) and Hariharan, Levi and Klein (2005) could be because, in the present study, the effect of the contour interaction was measured at the letter recognition thresholds obtained from the psychometric functions, unlike Levi, Klein and Hariharan (2002) and Hariharan, Levi and Klein (2005) who measured contour interaction effect for smaller and larger letter size targets but not at individual letter thresholds. The differences in the results indicate that the target size is an important element to be considered while measuring crowding or contour interaction effect.

Interestingly, in most of the studies that showed greater crowding or contour interaction in amblyopes, the effect was more exaggerated in strabismic amblyopes than anisometropic amblyopes (Stuart and Burian, 1962; Giaschi, Regan, Kraft and Kothe, 1993; Hess, Dakin, Tewfik and Brown, 2001; Levi, Klein and Hariharan, 2002; Bonneh, Sagi and Polat, 2004; 2007; Polat, et al., 2005) possibly due to greater positional uncertainty or distortion in strabismic amblyopes (Levi, Waugh and Beard, 1994; Hess and Field, 1994; Levi, Klein and Hariharan, 2002; Bonneh, Sagi and Polat, 2007). However, the results of the present study showed a similar extent of contour interaction at high contrast level in strabismic and anisometropic amblyopes and are hypothesised to be due to the decreased sensitivity of position uncertainty or gaze fixations using a SGRL chart (albeit in only one strabismic subject).

Further, consistent with the data of Simmers, Gray, McGraw and Winn (1999a), the results of the present study showed that the effect of contour interaction was less for the low contrast letters than the high contrast letters in non-amblyopic and amblyopic eyes. Our results are in agreement with the findings of Kothe and Regan (1990a) and Giaschi, Regan, Kraft and Kothe (1993) who found that the crowding was less for the low contrast than the high contrast letters in children and adults with normal vision. Less crowding with the low contrast letters was speculated to be due to the decreased interaction between the adjacent low contrast letters. Giaschi, Regan, Kraft and Kothe (1993) showed that in amblyopic children and adults, the crowding effect was variable. They suggested that amblyopia is not just the loss of the high contrast visual acuity but also includes low contrast visual deficit and suggested that visual acuity should be measured with high and low contrast letters. The discrepancies in Giaschi, Regan, Kraft and Kothe (1993) results in regards to crowding in amblyopes could be due to the differential influence of gaze instability or position uncertainty while fixating on each letter in the Snellen type chart and also could be due to the differential influence of attention needed to separate the surrounding letters for the target letter. However, such an influence of gaze instability and attentional component are minimal using a SGRL chart used in the present study and also in Simmers (Simmers, Gray, McGraw and Winn, 1999a) experiment where Sloan letters were surrounded by flanking bars. Unlike the Giaschi, Regan, Kraft and Kothe (1993) results, the minimal influence of gaze fixations and attention on visual thresholds in the stimuli used in the present study could be the reason for the consistent contour interaction effect found in amblyopes. Previous studies have also shown that the contrast sensitivity loss was different between strabismic (high spatial frequency loss) and anisometropic amblyopes (overall spatial frequency loss) (Hess and Howell, 1977; Abrahamson and Sjostrand, 1981; 1988; Bradley and Freeman, 1981). Also, strabismic amblyopes are not susceptible to the matching of edge blur of a stimulus or perceiving the changes in the contrast, while anisometropic amblyopes are prone to such deficits (Simmers, Bex and Hess, 2003). This finding was assumed to be due to differences in the neural basis of strabismic and anisometropic amblyopes (Ellemberg, Hess and Arsenault, 2002; Hess, Pointer, Simmers and Bex, 2003). Therefore, such a low contrast visual perception differences between strabismic and anisometropic amblyopes could be the reason why the strabismic amblyope in the present study had no difference in the recognition thresholds between the non-amblyopic eye and amblyopic eye unlike the anisometropic amblyopes of the present study.

Flom, Weymouth and Kahneman (1963) suggested that crowding in amblyopes is due to the involvement of larger cortical receptive field in amblyopic visual system, while other studies reasoned crowding to be due to the extended pooling or abnormal integration of the target and flankers (Levi, Klein and Hariharan, 2002; Pelli, Palomares and Majaj, 2004; Hariharan, Levi and Klein, 2005). Additionally, the decreased vision in strabismic amblyopes was speculated to be due to the decrease in the number of neurons (Levi and Klein, 1986) or due to the disarray in the spatial arrangement of neurons (Hess and Field, 1994) or due to the abnormal interactions between neurons (Polat, Sagi and Norcia, 1997).

Further, the process of letter identification in amblyopes has been studied in the past (Chung, Levi, Legge and Tjan, 2002; Pelli, Levi and Chung, 2004). Chung, Levi, Legge and Tjan (2002) measured the contrast thresholds needed to identify spatially filtered isolated letters. They noticed that the process of letter identification in relation to the spatial frequency characteristics was similar in amblyopic and non-amblyopic eyes when measured at visual acuity limits. Therefore, the scaling of contour interaction effect in the non-amblyopic and amblyopic eyes of the present study may be due to the similar process involved in the letter identification in both the subject groups.

On the other hand, previous studies have shown that an isolated optotype overestimates the relative visual acuity scores when compared to a linear or a whole letter chart in normal and amblyopic subjects. The sensitivity of the vision chart has to be increased in order to elicit amblyopia easily (Hilton and Stanley, 1972; Youngson, 1975; Rodier, Mayer and Fulton, 1985; Manny, Fern and Loshin, 1987; Atkinson, et al., 1988; Simmers, Gray and Spowart, 1997; Morad, Werker and Nemet, 1999; Elliott and Firth, 2007). Our findings suggest that the contour interaction effect reduces for the low contrast than the high contrast letters and therefore a high contrast letter chart with sensitivity to contour interaction rather than a low contrast letter chart would be better for use in screening for amblyopic vision.

Conclusion

In conclusion, the results of the present study support the notion of previous studies (see Stuart and Burian, 1962; Flom, Weymouth and Kahneman, 1963;

Simmers, Gray, McGraw and Winn, 1999a) that the crowding or contour interaction scales in normal and amblyopes when measured at individual thresholds. Also, contour interaction is contrast dependant and stronger for high contrast than the low contrast letters in non-amblyopic and amblyopic eyes.

Chapter 5

To investigate the effect of letter separation and gaze fixations between SG repeat and SG complex visual acuity measurements in normal and amblyopic vision

Introduction

In the 2nd, 3rd and 4th Chapters, the effect of contour interaction on high (80%) and low (5.8%) contrast repeat letters was investigated using SGRL charts in subjects with normal and amblyopic vision. The results showed a significant effect of letter separation on the repeat letter thresholds at both the contrast levels. The extent of contour interaction was at 0.2 letter width separation and maximum intensity was at the abutting condition in normal and amblyopic subjects. However, the repeat letter thresholds were less for the low contrast than the high contrast letters for all the separation conditions and for the normal and amblyopic subjects. This Chapter will focus on the effect of gaze fixations on visual thresholds in normal and amblyopic subjects.

In this Chapter, visual acuity scores are measured using a Sheridan Gardiner complex interaction (SGCI) chart that is similar in principle to Flom's S chart (Flom, Weymouth and Kahneman, 1963; Flom, 1991). The SGCI chart is presented at a range of inter-letter separations matching those used previously for the SGRL chart (Chapter 4). The visual thresholds are compared between the SG isolated letter, SGRL and SGCI thresholds. If as originally proposed by Flom, Weymouth and Kahneman (1963), crowding is due to a combination of contour interaction, gaze fixations and attention; it will be possible to uniformly disambiguate these factors by comparing the SGRL acuity and SGCI acuity.

We assume that SG isolated letter thresholds are not influenced by the effects of contour interaction and any effects of gaze instability and attention are relatively small. Similarly, the SGRL thresholds presented at a range of letter separations are also immune to the effects of gaze instability and attention. However, contour interaction has a significant effect at the closer letter separations. Relatively poor repeat letter acuity compared to isolated letter acuity, especially at the closer inter-letter separations are likely to be due to the effects of contour interaction on repeat letter thresholds, as observed in the results of Chapters 2, 3 and 4. On the other hand, the SGCI thresholds obtained when presented under different separation conditions could be affected by contour interaction, gaze instability and attention. However, the effect of contour interaction is assumed to be constant between the SGRL and SGCI thresholds due to the uniform letter separations used in both the charts. Any difference between the SGRL and the SGCI thresholds would therefore be due to the effects of gaze instability or attentional component.

In order to verify whether gaze instability or attentional components contribute to the crowding phenomenon, SGCI thresholds were also measured for inter-letter separations greater than 1.0 letter width. While it is known that the attentional component to crowding has little influence on identifying SG isolated and repeat letters at the fovea, if the SGCI thresholds for separations greater than 1.0 letter width are the same as thresholds for SG isolated and repeat letter targets at 1.0 letter width, it could be inferred that attention has a minimal role in identifying SGCI letters. On the other hand, attentional components may be a contributory factor towards visual crowding if the SGCI thresholds for separations greater than 1.0 letter width fail to achieve equitable threshold values compared to the SG isolated or SGRL thresholds at 1.0 letter separation. We therefore hypothesise that instability in gaze fixations have a greater contributory factor towards visual crowding if the SGCI thresholds are higher than the SGRL threshold at the uniform inter-letter separation measured. Further, analysis of the type of errors that subjects make (substitutional or random) at near (abutting and 0.2) and far (1.0 and greater than 1.0) inter-letter separations would predict a higher proportion of substitutional errors where gaze instability is a factor in the result. The mis-identification of the target letter by substituting one of the adjacent horizontal letters either to the right or left of the target letter was categorised as a substitutional error. All other errors were categorised as random errors.

Methods

Apparatus & Stimuli

The apparatus used in this experiment was the same as that described in Chapter 4. The stimuli were generated on a Dell computer using MATLAB software (The Math Works, MA) and displayed on a gamma corrected 17" monitor (Sony GDM-F520) using a CRS 2/5 graphics card. The mean luminance of the screen was 123cdm^{-2}. The optotypes used in the study were the seven Sheridan Gardiner letters. The individual letter optotypes were constructed with a stroke width of 3 pixels and a total diameter of 15 pixels. However, in the amblyopic eye of one subject (SR), the stroke width was increased to 7 pixels in order for them to reach 100% correct responses at the closest test distance. In this experiment, a series of SGCI charts was constructed based on the complex interaction S chart described elsewhere (Flom, Weymouth and Kahneman, 1963; Flom, 1991; Wick and Schor, 1984). The SGCI chart comprised a central 3 x 3 array of randomised Sheridan Gardiner letters. Each

SGCI chart was surrounded by an additional single letter array of a repeated SG letter (in this condition a letter O was chosen because of its symmetrical shape) making each array a dimension of 5 x 5 optotypes in total. The addition of the surrounding letter O was included to maintain equality of contour interaction for the outside randomised SG letters (see Figure 5.1). The inter-letter separations used were 1.0, 0.6, 0.4, 0.2 times the letter size and abutting matching those used previously in the SGRL chart (Chapter 4). In addition, SGCI thresholds were measured at inter-letter separations beyond 1.0 letter width (varied according to the subject).

Figure 5.1: Depicts SGCI charts at 1.0, 0.4 letter width separations and abutting.

O O O O O
O A X H O
O T V U O
O U X O O
O O O O O

O O O O O
O T X V O
O U A T O
O H V X O
O O O O O

OOOOO
OHVTO
OTOXO
OXAUO
OOOOO

Procedure

General condition

Three adult subjects with normal or corrected to normal visual acuity (of at least 6/6) and four amblyopic subjects (3 anisometropic amblyopes and 1 strabismic amblyope) who participated in the experiment described in the Chapter 4 took part in this experiment (see Table 4.1). Subjects viewed the monitor monocularly and in the case of the amblyopic subjects both the amblyopic and non-amblyopic eyes were tested. SGCI charts were presented in the middle of the monitor and for an unlimited viewing time. Subjects were required to fixate and identify each letter in the central 3 x 3 array starting from left to right in the 1st row followed by the 2nd and lastly the 3rd row. Responses were recorded by an examiner based on the subject's verbal response. A method of constant stimuli was used where the size of the letters was varied by varying the test distance according to a logarithmic scale. The testing distance covered a range of distances from the monitor in order to attain a guess rate to 100 % correct responses encompassing the psychometric function. The order of the test distances was chosen either from closer to further the monitor or vice-versa and the order was randomised between runs. The series of runs were randomised between the non-amblyopic and the amblyopic eyes. Sufficient practice was given to obtain consistent results and breaks were allowed in-between the runs to lessen fatigue. SGCI charts were presented at random in runs of 126 trials per separation condition, so that each individual SG letter and separation condition was presented 18 times per run.

The SGCI thresholds were compared to the isolated SG letter thresholds and SGRL thresholds. Also, for each of the stimulus conditions (SGRL chart and SGCI chart), each subject was tested with the same range of letter separations ranging from 1.0, 0.6, 0.4, 0.2 letter width separation and abutting for uniform comparison of thresholds at constant separation conditions. In the case of amblyopic subjects, the data for the isolated SG letters and SGRL chart were taken from the experiment described in Chapter 4. However, in case of the normal subjects, all three stimulus conditions (SG isolated letter chart, SGRL chart and SGCI chart) were experimented.

Control conditions

Analysis of errors

In addition to the main experiment, a control condition was performed to investigate the specificity of the origin of the errors made while identifying letters using a SGCI chart. Substitutional and random errors were determined based on subjects' nearby recognition thresholds. The data required to calculate the errors were obtained from the data of the main experiment (the percentage correct responses ranging between 53.19±4.22 that were obtained using a SGCI chart) (Table 5.1). The stimulus and responses were compared position by position and the errors were calculated using Microsoft Excel™. The errors were determined for all normal eyes and the amblyopic and non-amblyopic eyes of the amblyopes (all subjects participated in the main experiment of this Chapter) and at the narrower (abutting and 0.2 letter width) and wider (1.0 and greater than 1.0 letter width) separation conditions. The separations were chosen based on the results of the experiments described in

Chapters 2 and 4 where the effect of contour interaction was minimal at 1.0 letter width separation but had an effect at 0.2 letter width separation and the abutting condition.

Data analysis

The data analysis for the main experiment was the same as that described in Chapter 2. The percentages of correct responses obtained for each subject and each separation condition were entered into Microsoft Excel. The average of all 3 runs and their standard deviations were obtained. The data thus obtained were then entered in Igor Pro Software (Wavemetrics, Lake Oswego, Oregon, USA) and were fit using the Weibull function (Pelli, Robson and Wilkins, 1988) as described in Chapter 2. The thresholds and slopes thus obtained were entered into a standard statistical package SPSS for Windows, Release Version 16.0, (© SPSS, Inc., 2009, Chicago, IL, www.spss.com). A repeated measures ANOVA and post-hoc analysis using a Bonferroni test were performed as appropriate. F values were corrected by adjusting the degrees of freedom with Greenhouse-Geisser method for any violations of Mauchly's sphericity. A chi square test was used to analyse the relation between the substitutional and random errors.

Table 5.1: Percentage correct responses that correspond to nearby SGCI thresholds for normal, non -amblyopic and amblyopic eyes

Subjects		Normal	eyes		NAE				AE			
Separation		EO	J S	VV	AB	RC	VS	SR	AB	RC	VS	SR
Abutting		47.62	58.73	55.36	56.55	54.75	54.44	58.73	55.95	50	55.95	57.14
0.2		51.19	48.02	54.37	58.73	49.6	48.53	50.4	58.13	57.54	52.14	59.92
1		42.66	53.97	52.78	56.15	43.84	47.1	58.73	53.57	56.75	47.09	50.00
>1.0		_	50.4	49.6	52.38	54.29	54.76	55.56	53.97	56.35	48.81	54.76

Results

General condition

For the 3 normal subjects that participated in the study, the percentages of correct responses were plotted as a function of visual acuity (Figure 5.2). Each psychometric curve represented by different colour corresponds to the individual letter separation used in the experiment ranging from 1.0, 0.6, 0.4, 0.2 letter width separations and abutting condition. The data for the control condition (isolated) are also shown. The graphs shows the psychometric functions for the responses obtained when SGRL chart (Panel A) and SGCI chart (Panel B) were used. The shift in the psychometric curves towards lower visual acuity scores reflects that the maximum deterioration in the performance was at the abutting condition for both the charts.

Figure 5.2: The data representing a layout of psychometric curves for 3 normal subjects and for all the separation conditions measured. Panels A&B depict the psychometric functions obtained for the SGRL and SGCI charts respectively. The error bars represent ± 1SD.

A (SGRL chart) B (SGCI chart)

The effects of crowding on visual acuity can be determined by comparing the thresholds obtained from the psychometric curves with the letter separation conditions. The individual and mean SGRL and complex interaction thresholds and the normalised thresholds for the normal subjects are shown in Tables 5.2 and 5.3 respectively. Figure 5.3 shows a layout of each of the normal subjects absolute thresholds (in LogMAR) plotted as a function of inter-letter separation. The thresholds obtained using both the charts increased with decreasing inter-letter separation. The maximum increase in the thresholds was at the abutting condition for all the subjects and for both the charts. The SGCI thresholds were higher than the SGRL thresholds for nearly all the separation conditions indicating a greater influence of gaze instability and attention components of crowding at each of the letter separation measured. There was almost a constant difference between the repeat and complex interaction thresholds at each of the letter separation conditions. However, subject EO showed equal repeat and complex interaction thresholds at the 1.0 letter separation. On the other hand, the complex interaction thresholds were higher than the repeat letter thresholds up to 1.0 letter separation in subjects JS and VV. The SGCI threshold obtained for separations wider than 1.0 letter separation (2.0 and 3.0 letter separation for subjects JS and VV respectively) was equal to the SGRL thresholds at 1.0 letter separation.

Figure 5.3: Recognition threshold is plotted as a function of letter separation. The datum points in light blue, dark blue and fluorescent green represent SGRL thresholds, SGCI thresholds and SG isolated letter thresholds, respectively for the three normal subjects. The error bars represents ±1 SD.

Tables 5.2(A) and 5.2(B): Depicts the thresholds and the mean thresholds obtained for the SGRL chart and SGCI chart respectively for all the separations and isolated letter condition for the normal subjects.

A	Repeat	Letter	thresholds									
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
EO	-0.10	0.01	-0.21	0.01	-0.26	0.00	-0.28	0.00	-0.30	0.01	-0.31	0.01
JS	0.01	0.01	-0.13	0.01	-0.20	0.01	-0.22	0.00	-0.24	0.01	-0.27	0.01
VV	-0.09	0.02	-0.21	0.01	-0.25	0.00	-0.27	0.01	-0.25	0.00	-0.21	0.00
Mean	**-0.06**		**-0.18**		**-0.23**		**-0.26**		**-0.27**		**-0.27**	
Std error	**0.06**		**0.05**		**0.03**		**0.03**		**0.03**		**0.05**	

B	Complex	letter	thresholds									
Separation	Abutting		0.2		0.4		0.6		1.0		>1.0	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
EO	-0.02	0.01	-0.13	0.00	-0.18	0.01	-0.23	0.00	-0.28	0.01		
JS	0.10	0.00	-0.02	0.01	-0.08	0.00	-0.12	0.00	-0.16	0.01	-0.20	0.01
VV	-0.01	0.00	-0.10	0.01	-0.14	0.01	-0.18	0.01	-0.19	0.01	-0.23	0.01
Mean	**0.03**		**-0.08**		**-0.14**		**-0.18**		**-0.21**		**-0.21**	
Std error	**0.06**		**0.06**		**0.05**		**0.06**		**0.06**		**0.02**	

Tables 5.3(A) and 5.3(B): Depicts the normalised thresholds and the mean normalised thresholds obtained for the SGRL chart and SGCI chart respectively for all the separations and isolated letter condition for the normal subjects.

A	Normalised	Repeat	letter	thresholds		
Separation	Abutting	0.2	0.4	0.6	1.0	Isolated
Subjects						
EO	0.22	0.10	0.06	0.04	0.01	0.00
JS	0.28	0.14	0.07	0.05	0.02	0.00
VV	0.12	0.00	-0.03	-0.06	-0.04	0.00
Mean	**0.21**	**0.08**	**0.03**	**0.01**	**0.00**	**0.00**
Std error	**0.08**	**0.07**	**0.06**	**0.06**	**0.03**	**0.00**
B	Normalised	Complex	letter	thresholds		
Separation	Abutting	0.2	0.4	0.6	1.0	Isolated
Subjects						
EO	0.30	0.18	0.13	0.08	0.03	0.00
JS	0.37	0.25	0.18	0.15	0.11	0.00
VV	0.21	0.11	0.07	0.03	0.02	0.00
Mean	**0.29**	**0.18**	**0.13**	**0.09**	**0.05**	**0.00**
Std error	**0.08**	**0.07**	**0.06**	**0.06**	**0.05**	**0.00**

The data for the mean and the normalised mean (threshold value at each separation - isolated letter threshold value) for the SGRL and SGCI thresholds for the normal subjects are shown in Figure 5.4. The difference between the SGRL and SGCI thresholds was nearly constant across letter separation conditions. A regression analysis was carried out between the SGRL and complex interaction thresholds in subjects with normal vision. The difference in thresholds between the SGRL and SGCI was plotted as a function of inter-letter separation and is shown in Figure 5.4. Each point represents the mean difference between the SGCI and SGRL thresholds at each separation condition. The data were fit using a straight line function and the corresponding regression analysis showed that the slope of the line was not significantly different from zero ($p>0.05$).

A two factor within subject factorial ANOVA was performed for the normal subjects using letter separation and charts (SGRL and SGCI) as the main factors. There was a significant main effect of separation on recognition thresholds $F(1.15, 2.30) = 81.14$, $p < 0.01$ and a significant main effect of the type of chart on recognition thresholds $F(1, 2) = 48.22$, $p < 0.05$. There was no significant interaction effect between the range of letter separations used for analysis and type of the charts used in the study $F(1.21, 2.42) = 8.40$, $p > 0.05$.

Figure 5.4(A): The top panel depicts the mean thresholds plotted as a function of the letter separation. Each datum represents the SGRL (light blue) and SGCI (dark blue) thresholds for each separation condition and for normal eyes. The error bars represent ± 1 SE. The middle panel shows the mean normalised recognition thresholds plotted as a function of the letter separation. The error bars represent ± 1 SE. The bottom panel plots the difference between the complex and repeat thresholds and shows the regression line (slope=0).

Further, the estimates of slopes obtained from the psychometric curve fitting for each separation condition were analysed in normal subjects. Table 5.4(A) and 5.4(B) depicts the slopes and their means for the SGRL and the SGCI chart respectively. Figure 5.5 shows the mean slopes derived from the Weibull functions for SGRL and SGCI chart plotted as a function of the letter separation. At 1.0 letter separation, the mean slope values were nearly the same for the repeat and complex interaction chart. At 0.6 and 0.4 letter separation, the mean slope values were lower for the complex interaction chart than the repeat letter chart. Contrary, at the 0.2 letter separation and the abutting condition, the mean slope values were lower for the repeat letter chart than the complex interaction chart. A two factor within subject factorial ANOVA was done in normal subjects for the letter separation and chart type (SGRL and SGCI). There was no significant main effect of separation on slopes $F(1.14, 2.28) = 4.08$, $p > 0.05$ and no significant main effect of the type of charts on slope values $F(1, 2) = 12.97$, $p > 0.05$. In addition, no significant interaction effect was noticed between the separation and type of chart used in the study $F(1.10, 2.20) = 3.98$, $p > 0.05$.

Figure 5.5: Slope of the psychometric function is plotted as a function of letter separation. Each datum represents the mean slope value averaged across all the subjects and for each separation condition. The datum points in light blue, dark blue and green fluorescent represents the mean slope values for the SGRL, SGCI and SG isolated letter chart respectively. The error bars represent ±1 SE.

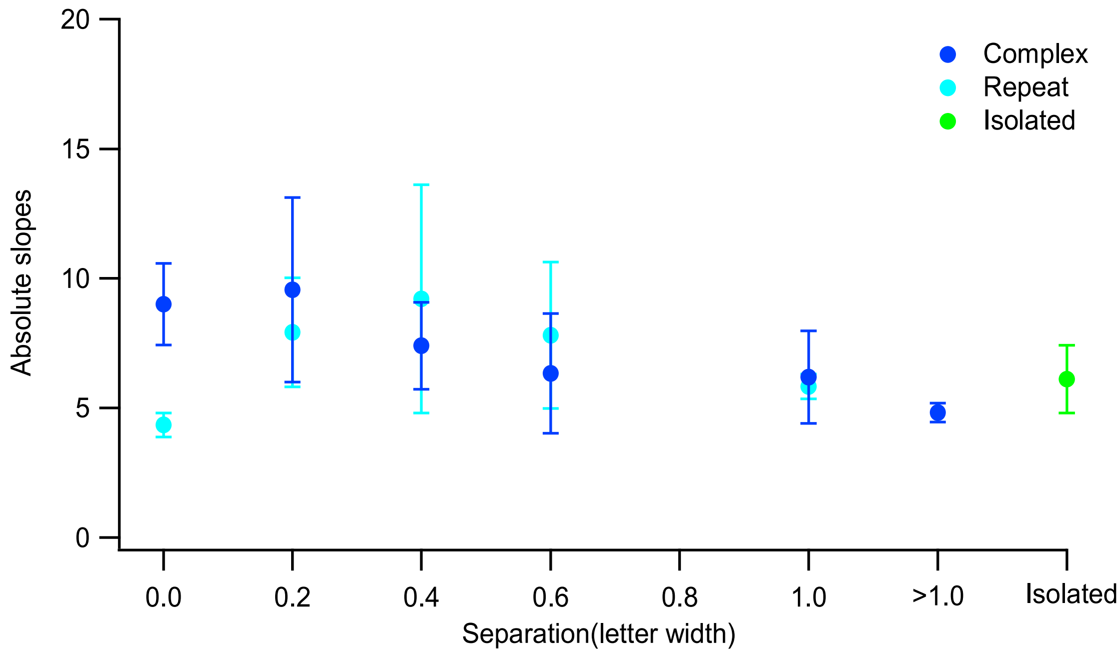


Table 5.4(A) and (B): Depicts the slopes obtained from the psychometric functions for the SGRL and SGCI chart respectively, for each individual subject and their means of all subjects for each separation condition and isolated letter condition.

A	Repeat	letter	thresholds									
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev
EO	4.76	0.55	9.88	2.24	14.13	2.23	10.86	1.21	6.36	1.02	7.05	0.81
JS	4.44	0.34	8.20	1.04	7.85	1.85	7.28	0.51	5.42	1.00	6.66	0.79
VV	3.84	0.80	5.71	0.70	5.65	0.21	5.29	0.88	5.71	0.36	4.64	0.16
Mean	**4.35**		**7.93**		**9.21**		**7.81**		**5.83**		**6.12**	
Std error	**0.47**		**2.10**		**4.40**		**2.82**		**0.48**		**1.30**	
B	Complex	letter	thresholds									
Separation	Abutting		0.2		0.4		0.6		1.0		>1.0	
Subjects	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev	Slope	Std dev
EO	10.82	2.83	13.68	0.79	8.27	1.29	8.95	0.91	8.24	2.75		
JS	8.05	0.44	7.49	1.32	8.47	0.70	5.50	0.37	5.21	0.36	4.57	0.36
VV	8.14	0.75	7.52	1.20	5.46	0.79	4.57	0.77	5.11	0.50	5.08	0.78
Mean	**9.00**		**9.56**		**7.40**		**6.34**		**6.19**		**4.82**	
Std error	**1.57**		**3.56**		**1.68**		**2.31**		**1.78**		**0.36**	

Amblyopic subjects

For the 4 amblyopic subjects the percentages of correct responses were plotted as a function of visual acuity and shown in Figure 5.6. The figure shows the psychometric functions for the responses obtained for the SGCI chart for the non-amblyopic (Panel A) and amblyopic eyes (Panel B). Shown in Figure 5.7, panel A&B is a comparison of the SG isolated letters, SGRL and SGCI thresholds for the non-amblyopic and amblyopic eyes respectively. The maximum increase in the thresholds was at the abutting condition for all the subjects and for both the charts. The SGCI thresholds were higher than the SGRL thresholds for all the separation conditions. The difference in the SGRL and SGCI thresholds was exaggerated in the amblyopic eye of the strabismic amblyope (SR) when compared to the 4 non-amblyopic eyes and for the amblyopic eyes of the 3 anisometropic amblyopes. SGCI thresholds for inter-letter separations greater than 1.0 letter width were approaching SGRL thresholds at 1.0 letter width separation in all 4 non-amblyopic eyes and 3 anisometropic amblyopic eyes. However, because of limitations in the specification of the monitor, construction of a SGCI chart at inter-letter separation greater than 3.8 letter widths for a larger pixel size was not possible and hence data for the strabismic amblyope (SR) could not be obtained at a wide enough inter-letter separation. The data for the SGRL and SGCI thresholds for the non-amblyopic and amblyopic eyes are shown in Tables 5.5 and 5.6 respectively. The mean data for the non-amblyopic and amblyopic eyes was not shown due to the individual differences between the amblyopic subjects especially in the amblyopic eyes. This is clearly seen in the amblyopic eye data shown in Table 5.6 where the standard errors for the mean repeat and mean complex interaction thresholds were considerably larger than the standard error obtained with the non-amblyopic eye data shown in Table 5.5.

Figure 5.6: The data represents a layout of psychometric curves for 4 amblyopic subjects and for all the separation conditions measured. Panels A&B represent psychometric functions obtained using a SGCI chart for the non-amblyopic and amblyopic eyes respectively. Each datum point was the average of at least three runs of 126 trials at each distance measured. Error bars represent ± 1SD.

A (non-amblyopic eyes) B (amblyopic eyes)

Figure 5.7: Recognition threshold is plotted as a function of separation in letter widths. Panel A and B represent the data for non-amblyopic (blue datum points) and amblyopic eyes (red datum points) respectively. The hollow and solid datum points represent SGRL thresholds and SGCI thresholds respectively. The data for the isolated letter condition (fluorescent colour) are also shown for all the amblyopic subjects. The error bars represents ±1 SD.

A (non-amblyopic eyes) B (amblyopic eyes)

The difference in thresholds between the SGRL and SGCI chart was plotted as a function of the inter-letter separation and is shown in Figure 5.8 for each individual subject and separately for the non-amblyopic (panel A) and amblyopic eyes (panel B). The data were fit using a straight line function and the regression analysis for each subject and for both the non-amblyopic and amblyopic eyes revealed that the slope of each line was not significantly different from zero ($p>0.05$).

A two factor within subject factorial ANOVA was performed for the non-amblyopic eyes using letter separation and charts (SGRL and SGCI) as main factors. There was a significant main effect of separation on recognition thresholds $F(1.54, 4.60) = 260.85$, $p < 0.01$ and a significant main effect of the type of chart on recognition thresholds $F(1, 3) = 424.63$, $p < 0.01$. No significant interaction effect was noticed between letter separations and type of chart $F(1.34, 4.02) = 1.45$, $p > 0.05$. Further, a two factor within subject factorial ANOVA was done for the amblyopic eyes for the separation and charts (SGRL and SGCI). There was a significant main effect of separation on recognition thresholds $F(1.31, 3.94) = 389.18$, $p < 0.01$ and no significant main effect of type of chart on recognition thresholds $F(1, 3) = 5.29$, $p > 0.05$. In addition, no significant interaction effect was noticed between the range of letter separation separations used for analysis and type of the charts $F(1.51, 4.52) = 2.60$, $p > 0.05$.

Figure 5.8: The difference between the complex and repeat letter thresholds is plotted as a function of separation in letter widths. Panel A and B represents the linear regression data for non-amblyopic (blue datum points) and amblyopic eyes (red datum points) respectively. Each point represents the difference between the SGCI thresholds and SGRL thresholds at each separation condition (slope=0).

A (non-amblyopic eyes) B (amblyopic eyes)

Tables 5.5(A) and 5.5(B): Depicts the thresholds and the mean thresholds obtained for the SGRL chart (obtained from the data of the experiment described in Chapter 4) and SGCI chart respectively for all the separations and isolated letter condition for the non-amblyopic eyes of all the subjects.

A	Repeat	letter	thresholds									
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
AB	-0.12	0.01	-0.22	0.01	-0.27	0.01	-0.31	0.00	-0.35	0.00	-0.30	0.01
RC	0.06	0.01	-0.07	0.01	-0.14	0.02	-0.19	0.00	-0.21	0.00	-0.20	0.01
VS	-0.05	0.01	-0.17	0.01	-0.21	0.01	-0.33	0.01	-0.27	0.01	-0.23	0.01
SR	0.03	0.03	-0.08	0.01	-0.14	0.01	-0.20	0.01	-0.19	0.01	-0.16	0.02
Mean	**-0.02**		**-0.14**		**-0.19**		**-0.25**		**-0.25**		**-0.22**	
Std error	**0.08**		**0.07**		**0.06**		**0.07**		**0.07**		**0.06**	

B	Complex	letter	thresholds									
Separation	Abutting		0.2		0.4		0.6		1.0		>1.0	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
AB	0.08	0.00	-0.09	0.00	-0.15	0.01	-0.20	0.00	-0.25	0.00	-0.30	0.00
RC	0.17	0.00	0.04	0.01	-0.02	0.00	-0.06	0.00	-0.11	0.00	-0.21	0.01
VS	0.07	0.00	-0.01	0.00	-0.07	0.00	-0.13	0.01	-0.17	0.01	-0.24	0.01
SR	0.16	0.00	0.04	0.01	-0.03	0.00	-0.06	0.01	-0.09	0.01	-0.20	0.01
Mean	**0.12**		**-0.01**		**-0.07**		**-0.11**		**-0.15**		**-0.24**	

Std error	**0.05**	**0.06**	**0.06**	**0.07**	**0.07**	**0.05**

Tables 5.6(A) and 5.6(B): Depicts the thresholds and the mean thresholds obtained for the SGRL chart (obtained from the data of the experiment described in Chapter 4) and SGCI chart respectively for all the separations and isolated letter condition for the amblyopic eyes of all subjects.

A	Repeat	letter	thresholds									
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
AB	-0.01	0.02	-0.16	0.01	-0.19	0.01	-0.22	0.01	-0.25	0.01	-0.17	0.01
RC	0.34	0.03	0.16	0.01	0.11	0.01	0.08	0.01	0.06	0.01	0.10	0.00
VS	0.15	0.02	0.00	0.01	-0.06	0.00	-0.09	0.00	-0.09	0.00	-0.10	0.01
SR	0.28	0.02	0.11	0.01	0.05	0.01	-0.02	0.02	-0.03	0.02	-0.09	0.01
Mean	**0.19**		**0.03**		**-0.02**		**-0.06**		**-0.08**		**-0.06**	
Std error	**0.16**		**0.14**		**0.13**		**0.13**		**0.13**		**0.12**	

B	Complex	letter	thresholds									
Separation	Abutting		0.2		0.4		0.6		1.0		>1.0	
Subjects	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev	Threshold	Std dev
AB	0.21	0.00	0.07	0.00	0.01	0.01	-0.04	0.00	-0.07	0.00	-0.24	0.01
RC	0.33	0.01	0.24	0.00	0.21	0.01	0.16	0.00	0.13	0.00	0.03	0.01
VS	0.24	0.00	0.15	0.01	0.09	0.01	0.03	0.00	0.04	0.00	-0.08	0.01

SR	0.72	0.02	0.62	0.02	0.57	0.01	0.55	0.03	0.48	0.02	0.16	0.01
Mean	**0.37**		**0.27**		**0.22**		**0.18**		**0.15**		**-0.03**	
Std error	**0.24**		**0.24**		**0.25**		**0.26**		**0.24**		**0.17**	

For the amblyopic subjects, a three way ANOVA showed a significant main effect of the letter separation on the repeat and complex interaction thresholds $F(1.07, 3.21) = 571.01$, $p < 0.01$.There was a significant main effect of chart type on recognition thresholds $F(1, 3) = 12.97$, $p < 0.05$. There was also a significant main effect of eye (NAE and AE) on recognition thresholds $F(1, 3) = 16.46$, $p < 0.05$. There was no significant interaction effect between the letter separation and the chart $F(1.31, 3.94) = 1.07$, $p > 0.05$. There was no significant interaction effect between the letter separation and the eye $F(1.56, 4.67) = 1.26$, $p > 0.05$. There was no significant interaction effect between the chart and the eye $F(1, 3) = 1.02$, $p > 0.05$. Finally, the interaction between letter separation x chart x eye was not significantly different $F(1.39, 4.18) = 5.34$, $p > 0.05$. Further, the estimates of slopes obtained from the psychometric curve fitting for each separation condition were analysed. Tables 5.7(A&B) and 5.8(A&B) depicts the individual slopes and their means for the SGRL and SGCI chart for the non-amblyopic and amblyopic eyes respectively. A two factor within subject's factorial ANOVA was done for the non-amblyopic eyes for the letter separation and charts (SGRL and SGCI). There was no significant main effect of the separation on slopes $F(1.54, 4.61) = 1.59$, $p > 0.05$ and no significant main effect of the type of chart on slope $F(1, 3) = 3.05$, $p > 0.05$. No significant interaction effect was noticed between the separation and type of the charts $F(1.86, 5.57) = 2.98$, $p > 0.05$. A two factor within subject factorial ANOVA for the amblyopic eyes for the separation and charts (SGRL and SGCI) showed no significant main effect of the separation on slopes $F(1.18, 3.54) = 0.50$, $p > 0.05$ and no significant main effect of the type of chart on slopes $F(1, 3) = 0.00$, $p > 0.05$. A significant interaction effect was noticed between the separation and the type of the charts $F(1.68, 5.05) = 7.19$, $p < 0.05$.

Tables 5.7(A) and 5.7(B): Depicts the slopes and the mean slopes obtained for the SGRL chart (obtained from the data of the experiment described in Chapter 4) and SGCI chart respectively for all the separations and isolated letter condition for the non-amblyopic eyes of all subjects.

NAE												
(A)	Repeat	letters										
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev
AB	1.89	0.15	4.60	0.55	5.46	0.56	6.79	0.23	7.27	0.72	5.24	0.64
RC	2.66	0.19	5.17	0.74	10.07	5.24	8.50	0.94	6.89	0.52	4.61	0.32
VS	3.54	0.51	8.12	1.33	3.81	0.48	11.02	4.35	4.73	0.63	4.87	0.35
SR	4.08	1.46	6.99	1.45	6.51	0.92	12.04	1.99	5.92	1.10	3.70	0.81
Mean	**3.04**		**6.22**		**6.46**		**9.59**		**6.20**		**4.61**	
Std error	**0.96**		**1.63**		**2.65**		**2.39**		**1.13**		**0.65**	
(B)	Complex	letters										
Separation	Abutting		0.2		0.4		0.6		1.0		>1.0	
Subjects	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev
AB	4.90	0.14	11.01	0.34	7.69	0.82	10.54	1.64	6.99	0.72	5.31	0.35
RC	6.77	0.37	6.70	0.79	7.63	0.86	6.65	0.00	10.89	1.30	9.59	1.71
VS	13.77	0.00	9.41	0.00	5.75	0.25	7.12	1.14	6.61	1.48	5.52	0.94
SR	6.92	0.36	6.48	1.03	7.62	0.93	5.81	0.65	5.22	0.53	5.88	0.89
Mean	**8.09**		**8.40**		**7.17**		**7.53**		**7.43**		**6.58**	
Std error	**3.90**		**2.19**		**0.95**		**2.08**		**2.43**		**2.02**	

Tables 5.8(A) and 5.8(B): Depicts the slopes and the mean slopes obtained for the SGRL chart (obtained from the data of the experiment described in Chapter 4) and SGCI chart respectively for all the separations and isolated letter condition for the amblyopic eyes of all subjects.

AE												
(A)	Repeat	letters										
Separation	Abutting		0.2		0.4		0.6		1.0		Isolated	
Subjects	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev
AB	2.01	0.21	5.49	0.61	10.39	2.07	7.38	1.14	6.28	0.71	4.62	0.53
RC	1.77	0.27	5.55	0.82	6.64	1.09	6.51	1.29	5.51	0.74	4.06	0.24
VS	3.32	0.78	5.26	0.53	6.81	0.33	5.86	0.53	9.56	0.75	6.00	1.19
SR	2.33	0.36	3.08	0.28	3.12	0.32	4.02	0.95	3.75	0.87	5.26	0.48
Mean	**2.36**		**4.85**		**6.74**		**5.94**		**6.27**		**4.99**	
Std error	**0.68**		**1.18**		**2.97**		**1.42**		**2.44**		**0.83**	
(B)	Complex	letters										
Separation	Abutting		0.2		0.4		0.6		1.0		>1.0	
Subjects	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev	Slope	stdev
AB	6.25	0.44	6.51	0.37	5.32	0.68	4.92	0.31	4.82	0.15	5.54	1.04
RC	7.26	0.96	6.56	0.56	5.66	0.52	5.52	0.21	5.53	0.52	4.87	1.06
VS	12.37	0.21	5.34	0.60	4.99	0.66	6.25	0.06	5.08	0.15	7.82	2.05
SR	2.82	0.46	2.28	0.27	2.49	0.27	2.30	0.40	2.24	0.39	2.64	0.22
Mean	**7.18**		**5.17**		**4.61**		**4.75**		**4.42**		**5.22**	
Std error	**3.95**		**2.01**		**1.44**		**1.72**		**1.48**		**2.13**	

Control condition

Error analysis

Data depicting the percentage responses obtained at or near the SGCI thresholds for correct responses, substitution response errors and random response errors were plotted as histograms for selected inter-letter separations (near (abutting and 0.2) and far (1.0 and greater than 1.0)) for all subjects (Figure 5.9 A & B). We hypothesised that the effect of inaccurate gaze fixation on or the lack of it on contour interaction are more likely to be apparent at these separations.

At all the separations measured, the percentage of the random errors was greater than the substitution errors in 3 normal eyes, 4 non-amblyopic eyes and 2 amblyopic eyes (2 anisometropic). The remaining 2 amblyopic eyes (1 strabismic (SR) and 1 anisometropic (AB)) showed a greater proportion of substitution errors than the random errors. Principally, the proportion of substitutional errors increased as the inter-letter separations decreased (Appendix 4). The data were analysed using Pearson's chi-square (χ^2) non-parametric test. There was a significant association between the probability of the expected and obtained responses for both the error types, at all the separation conditions and for all subjects ($p<0.001$). The value of χ^2 varied between 25.55 and 34.12 under different test conditions. The obtained odd ratios showed that the normal, non-amblyopic and amblyopic eyes are more likely to make substitution errors by 0.79, 0.83 and 1.41 times respectively.

This true data are masked as our method of error analysis seems to be biased in favour of making more random errors.

Figure 5.9: The histograms plot the proportion of correct responses, substitution errors and random errors for the selected inter-letter separations for three normal subjects (A) and four amblyopic subjects (B). The error bars represents ± 1 SD.

Figure 5.9 (A):

Figure 5.9 (B):

Discussion

The current experiment investigated the effect of gaze fixations on crowding in normal, non-amblyopic and amblyopic eyes. The results showed a significant effect of the letter separation, chart type and eyes on recognition thresholds. The SGCI thresholds were higher than the SGRL thresholds at all the separation conditions and for normal, non-amblyopic and amblyopic eyes. While it is known that the SGRL acuity is less sensitive to gaze fixations and attention components, the higher SGCI threshold at each separation condition is attributed to the additional requirement of gaze fixations and attention component while making sequential saccadic eye movements to identify each letter in the SGCI chart. The difference between the SGRL and complex interaction thresholds may be due to gaze fixation and attention for separations ranging from 0.4 to 1.0 letter separations. Additionally, contour interaction plays a role for separations less than 0.4 letter widths as observed from the results of experiments described in Chapters 2, 3 and 4. However, the effect of contour interaction is coordinated both in the repeat and complex interaction thresholds for separations less than 0.4 letter width separation. Further, the difference between the SGRL and complex interaction thresholds was constant for separations ranging from abutting to 1.0 letter separation. This is an important finding because, the consistent difference between the repeat and the complex interaction thresholds suggest an equal effect of any instability in gaze fixations and attention on visual thresholds at the wider and narrower letter separations. However, subject EO showed nearly the same SGRL and SGCI thresholds at 1.0 letter separation. Therefore, for subject EO, the SGCI thresholds were not affected by gaze instability and attention at 1.0 letter separation.

Further, the SGCI threshold for a separation greater than 1.0 letter separation attained nearly the same threshold values as the SG isolated letter and SGRL at 1.0 letter separation. We had earlier assumed any differences in threshold between the three charts at these extended inter optotype letter separation may be due to attention deficits. Consequently at optotype separations greater than 1.0 letter spacing the effect of contour interaction, inaccurate gaze fixation and attention become negligible or insignificant resulting in threshold values that are similar to that obtained with the isolated SG letters. We therefore attribute a greater influence of gaze fixations rather than attention component as a contributory factor towards visual crowding when SGCI chart was used.

This result is consistent with the finding of Flom (1991) who highlighted the influence of gaze fixations rather than attention on visual crowding. Flom (1991) measured visual acuity using an isolated optotype E and a complex stimuli (a central E surrounded by C’s which are further surrounded by E’s at 0.4 letter width separation). The flanking C’s and E’s have provided distraction from identification of the central optotype E. The assumption was that this complex arrangement would require greater attention to identify the target central E. However, the results of the study showed that visual acuity was nearly the same with the isolated E and complex E stimuli. Consequently, Flom (1991) stated that attention has minimal or no role on crowding especially when measuring visual acuity at fovea. Later, Leat, Li and Epp (1999) also found that attention has a minimal role on visual acuity when stimuli were presented at the fovea. The current results agree with these earlier reports.

Based on these findings, we attribute inaccurate gaze fixations as the major contributor to the perceptual difficulties associated with the phenomenon of crowding in visual acuity measured using a whole letter chart.

The results also implied a greater percentage of substitution errors at narrower inter letter separations. Based on our analytical method, the probability of making random errors (4 out of 6 SG letters) is higher than the probability of making substitution errors (2 out of 6 SG letters). Consequently, our method is biased (about 3 times) in favour of making more random errors. This may have masked any contribution of substitution errors. However, a chi-square analysis has depicted the true effect of substitutional errors towards gaze instability. Further, the substitutional errors are restricted only to the flanking letters that are to the immediate right or left of the target letter. However, overshooting of saccadic fixations may be greater especially in amblyopic eyes and would result in fixating on a letter not just in the immediate vicinity of the target letter. A careful look at Figure 5.9B shows that the strabismic amblyope (SR) demonstrated a higher percentage of substitution errors than random error at all distances except at separations greater than 1.0 letter width separation. This may be due to position uncertainty associated with inaccurate fixation eye movements in strabismus amblyopia (Levi and Klein, 1982, 1983; Bedell, Flom and Barbeito, 1985; Levi, Klein and Yap, 1987; Barbeito, Bedell and Flom, 1988). Further, a greater difference in the SGRL and SGCI thresholds in amblyopic eyes than the non-amblyopic and normal eyes could be due to the greater influence of gaze instability on visual thresholds in amblyopic eyes.

Our results are comparable to the previous studies that compared isolated letter acuity, repeat letter acuity and Snellen acuity in normal children (Kothe and Regan, 1990b) and in normal and amblyopic children and adults (Regan, Giaschi, Kraft and Kothe, 1992). Both the studies used a repeat letter chart and a Snellen type chart that has 1.0 letter width separations and the effect of gaze instability on visual thresholds at closer separations was not studied. The results of both these previous studies showed that some subjects had better repeat letter acuity than the Snellen acuity and vice-versa while other subjects showed no significant difference between the repeat and the Snellen acuity. Unlike the results of previous studies, the results of the present study showed higher SGCI thresholds than the SGRL thresholds for all the subjects and all the separations measured. This difference in the results between the previous and the present study could be due to the non-uniform crowding in the Snellen type chart when compared to the SGCI chart used in the present study. This is also evident from the results of other studies where amblyopic visual acuity was best measured with the complex interaction S chart designed by Flom, Weymouth and Kahneman (1963) or a PVA test (psychophysical testing target) designed by Davidson and Eskridge (1977) that has a uniform chart design leading to uniform crowding (see Wick and Schor, 1984; Davidson and Eskridge, 1977). Further, the comparison between the SGRL thresholds and the SGCI thresholds was at uniform and constant separations leading to consistent results between the subjects.

Previous studies showed that the poor Snellen type acuity (Kothe and Regan, 1990b; Regan, Giaschi, Kraft and Kothe, 1992), Glasgow acuity (Simmers, Gray and Spowart, 1997), multiple E optotype acuity (Stuart and Burian, 1962) and complex interaction S acuity (Flom, Weymouth and Kahneman, 1963) or linear array E optotype acuity (Maraini, Pasino and Peralta, 1963) was assumed to be due to the influence of unsteady gaze fixations while fixating on each optotype in the chart. The error analysis of the present study support the idea that substitutional errors are more frequent especially at narrower letter separations and in normal, non-amblyopic and amblyopic eyes. This confirmation seems robust in the strabismic amblyopic eye (SR) and may possibly be due to the position uncertainty in strabismic amblyope (Bedell, Flom and Barbeito, 1985; Barbeito, Bedell and Flom, 1988; Flom and Bedell, 1985).

On the other hand, some studies attributed letter confusion and contour interaction as a causative factor for crowding mainly at narrower letter separation (Liu and Arditi, 2000). Though the influence of the letter confusions for SG isolated letters, repeat and complex interaction thresholds was assessed at wider and narrower letter separations, not much information was available to support the influence of letter confusion on visual thresholds (see Appendix 5).

Conclusion

To summarise, the results of this experiment confirm that a relative instability in gaze fixations is an important and significant factor in visual crowding for foveal letter chart targets. This was the same in normal, non-amblyopic and amblyopic eyes. Further, the difference between the repeat and the complex interaction thresholds was constant at all the separations indicating a consistent influence of gaze fixations at each separation condition. Further, substitutional errors did show an influence especially at closer separations thus supporting the role of unsteady gaze fixations as a reason for poorer visual acuity scores (Bedell, Flom and Barbeito, 1985; Barbeito, Bedell and Flom, 1988; Flom and Bedell, 1985). On the other hand, our letter confusion analysis did not provide enough evidence to support the role of letter confusion towards crowding.

Though numerous charts have been designed by incorporating the contour interaction element in the form of flanking bars or flanking letters, as a prerequisite to increase the sensitivity of the chart to elicit amblyopia easily, the results of the present experiment show that the involvement of gaze fixations rather than contour interaction or attention is an important factor to be considered while designing vision charts. Therefore, a vision chart with incorporated gaze fixations would be ideal to measure visual acuity than with a chart that incorporates contour interaction but doesn't involve a gaze fixation element. This may have a clinical implication to precisely design vision charts to elicit amblyopia effortlessly.

Chapter 6

Summary and conclusions

The overall aim of this thesis was to systematically distinguish between the effects of contour interaction, contrast and gaze fixations on visual thresholds. This would aid to better understand the factors affecting visual crowding in particular to vision charts.

Chapter one described the different kinds of vision charts available to measure visual acuity in adults and children and the drawbacks with commonly used vision charts. The literature highlighted that during vision assessments, young children can be easily distracted and as a result, visual acuity is often measured using single letters (or pictures). However, the use of single letters makes the visual acuity task easier because it eliminates the crowding effect, the well-known decrease in visual acuity due to the presence of surrounding features. Crowding is thought to be due to result from the sum of a number of factors including contour interaction, contrast, gaze instability and attention (Flom, 1991). The phenomenon of crowding has been studied as a single entity, but fewer studies have segregated the factors affecting crowding (Kothe and Regan, 1990b). This thesis is an attempt to uniformly segregate and to precisely study the effect of contour interaction, contrast and gaze instability on crowding.

Firstly, previous studies investigated the effect of contour interaction on visual thresholds using optotypes surrounded by flanking bars. However, whole letter charts such as the Snellen or LogMAR chart that are widely used to measure visual acuity in clinical practice consists of flanking letters and not flanking bars. It would therefore be preferable to study the contour interaction effect using flanking letters rather than flanking bars. Secondly, Flom, Weymouth and Kahneman (1963) described crowding as a combination of contour interaction, gaze fixations and attention. To solely study the effect of contour interaction on crowding, factors such as gaze fixations and attention have to be minimised. These above mentioned criteria necessitates the need to study the effect of contour interaction on visual thresholds using a whole letter chart design where contour interaction is induced using flanking letters and visual acuity obtained with such a chart is less sensitive to any effect of gaze instability and attentional factors. One such chart that satisfies the criteria of having multiple optotypes and that is less sensitive to the effects of erroneous gaze instability is a Regan repeat letter chart designed by Kothe and Regan (1990b).

The effect of contour interaction on visual thresholds was studied using a Sheridan Gardiner repeat letter (SGRL) chart. The SGRL chart (Figure 2.1) consists of the same SG letter repeated in a 7x7 array with a row of randomised SG letters at the periphery of the chart to maintain contour interaction for the outside repeated letters. The SGRL chart was constructed at separations ranging from the abutting to 1.0 letter width separation thereby inducing the contour interaction component. The subject's task was to identify the repeated letter within the array. Consequently, the detrimental effect of gaze instability on letter identification is minimised or even eliminated. Also, because the letters in the array are the same, any fixation inaccuracies will not lead to verbalization of a different letter. Thus, the SGRL chart at a range of separations solely allows studying the effect of contour interaction on visual thresholds.

Chapter Two described the first series of experiments where the effect of contour interaction on visual acuity was investigated using the high contrast (80%) SGRL chart in subjects with normal vision. Visual thresholds were measured using a high contrast SGRL chart that is less sensitive to the effects of gaze instability and attentional components (Kothe & Regan, 1990b). The SGRL acuity was reduced with decreased inter-letter separation indicating the presence of a contour interaction effect for separations less than 0.2 letter widths. The maximum increase in the thresholds at the abutting condition could possibly be due to the lack of the detailed detection of letter features at closer separation resulting in an increased response bias and increased contour interaction at the closest target flanker separation.

A control experiment (comparing SGRL acuity using two different array sizes, 7x7 and 3x3 arrays) confirmed that the visual thresholds measured at different letter separations and test distances were not influenced by the change in the angular size of the array at different test distances measured. Further, the results showed an effect of the letter type on contour interaction. Letters T and H were easier to identify and were less sensitive to contour interaction when compared to rest of the Sheridan Gardiner letters. This may have clinical implication and emphasise the importance of considering equally legible letters when designing vision charts. From the results of the 2nd Chapter it may be concluded that when visual thresholds are less sensitive to gaze instability and attention component, the effect of contour interaction on SGRL thresholds occurs between 0.2 letter separation and abutting condition.

Chapter Three described the effect of contour interaction on low contrast (5.8%) SGRL acuity in subject's with normal vision. Though previous studies have investigated the effect of contrast on crowding (Kothe and Regan, 1990a; Giaschi, Regan, Kraft and Kothe, 1993), the findings of the previous studies (Kothe and Regan, 1990a; Giaschi, Regan, Kraft and Kothe, 1993) may not be explained solely by contour interaction as the Snellen type chart used in both the studies includes a combination of contour interaction, gaze fixation and attention components. This Chapter has solely investigated the effect of contour interaction on visual thresholds using low contrast SGRL chart attempting to keep the effect of gaze fixations and attention to minimal. The results showed that contour interaction for the low contrast targets was demonstrable at the abutting condition. The findings of Chapter 2 and 3 show that contour interaction effect is dependent on the contrast of the stimuli and is present in both the high and low contrast letters but is less for the low contrast letters.

Chapter Four investigated the effect of contour interaction on high (82%) and low contrast (8 -16%) SGRL acuity in subject’s with amblyopic vision. It would be important to study the effect of contour interaction and contrast in amblyopes especially due to their reduced visual acuity and contrast sensitivity. The extent of contour interaction was at 0.2 letter width separation and the maximum intensity was at the abutting condition in the non-amblyopic and amblyopic eyes and at both the contrast levels. However, the effect of contour interaction was less for the low contrast than the high contrast condition in both the non-amblyopic and amblyopic eyes. Contrary to the high contrast condition, the amblyopic eyes were less affected than the fellow non-amblyopic eyes when contour interaction was determined at the low contrast condition. This shows that the amblyopic eyes are less prone to contour interaction at the low contrast stimuli condition. Further, the magnitude of contour interaction scaled with the isolated visual acuity scores for the non-amblyopic and amblyopic eyes especially at the high contrast level. The findings of this Chapter suggest that a high contrast letter chart with sensitivity to contour interaction than a low contrast letter chart would be better for use in measurements of amblyopic vision.

Chapter Five encompass a key part of this thesis and investigated the effect of contour interaction and gaze fixations on visual thresholds and in subjects with normal and amblyopic vision. A Sheridan Gardiner complex interaction (SGCI) chart (Figure 5.1) at a range of letter separations was used to measure visual acuity. The SGCI chart was constructed based on the complex interaction S chart described elsewhere (Flom, Weymouth and Kahneman, 1963; Flom, 1991; Wick and Schor, 1984). The SGCI chart comprised a central 3 x 3 array of randomised Sheridan Gardiner letters. Each SGCI chart was surrounded by an additional single letter array of a repeated SG letter (in this condition a letter O was chosen because of its symmetrical shape) making each array a dimension of 5 x 5 optotypes in total. The addition of the surrounding letter O was included to maintain equality of contour interaction for the outside randomised SG letters (see Figure 5.1). The inter-letter separations used were 1.0, 0.6, 0.4, 0.2 times the letter size and abutting matching those used previously in the SGRL chart (Chapter 4). Subjects were required to fixate and identify each letter in the central 3 x 3 array starting from left to right in the 1st row followed by the 2nd and lastly the 3rd row. Due to the constant separations used in both the charts, it is hypothesised that any difference between the SGRL and the SGCI thresholds would be due to the effects of gaze instability or attentional components. The SGCI thresholds were higher than the SGRL thresholds for separations ranging from abutting to 1.0 letter width separation and for normal, non-amblyopic and amblyopic eyes, except for subject EO who showed nearly the same SGRL and SGCI thresholds at 1.0 letter width separation. Also, the difference between the SGRL and SGCI thresholds was constant across the letter separations measured (abutting to 1.0 letter width separation), indicating a uniform effect of gaze fixations at the measured separations. However, the

SGCI thresholds when measured for separations greater than 1.0 letter width were similar to the SGRL threshold at 1.0 letter width separation and the isolated letter condition. This may infer that attention has a minimal role in identifying SGCI letters considering the fact that the attentional component has little influence on identifying SG isolated and SG repeat letters. Further, an error analysis was performed to investigate the influence of gaze instability at different separation conditions. The mis-identification of the target letter by substituting one of the adjacent horizontal letters either to the right or left of the target letter was categorised as a substitutional error. All other errors were categorised as random errors. The error analysis predicted a greater influence of substitution error than random error especially at the closer letter separations. The substitution error was more prominent in the strabismic amblyope indicating a potential influence of gaze instability as a causative factor for reduced visual acuity. Further, the letter confusion analysis was obtained for the SGRL and SGCI thresholds but was ineffective to explain visual crowding.

In conclusion, this thesis has shown that visual acuity scores are greatly influenced by gaze fixations and is evident from the increased SGCI than the SGRL thresholds. The sensitivity of vision charts may be increased by requiring patients to read letters across a line in order to ensure that a gaze fixation element is present in the measured acuity. A vision chart sensitive to gaze fixations than contour interaction may be ideal to measure visual acuity especially to screen for amblyopia.

Future work

The results of this thesis confirm that the sensitivity of vision chart may be increased by induced gaze fixations than contour interaction element. Though the rationale hypothesises minimal influence of attentional component towards visual crowding, the effect of attention component on visual crowding was not examined in this thesis. Therefore further research could include

1. Investigating the effect of attentional component on visual acuity in normal and amblyopic adults. This could be done by designing a chart similar to the SGCI chart and at a range of letter separations. However, the subject's task would be to identify the letter in the middle of the chart. The task will not involve any induced gaze fixations but will induce attentional component as the subject would have to concentrate and pay more attention on the middle letter alone though being distracted by the flanking letters.

2. Systematic investigation of the importance of contour interaction, gaze fixations and attentional component in normal and amblyopic children.

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Appendices

Appendix 1: Depicts the pictures of Cambridge Crowding cards, Kay pictures, Lea symbols, HOTV and Glasgow acuity cards. The picture is adapted from http://www.journalofoptometry.org/sites/default/files/elsevier/images/310/310v02n01/grande/310v02n01-13188760fig3.jpg

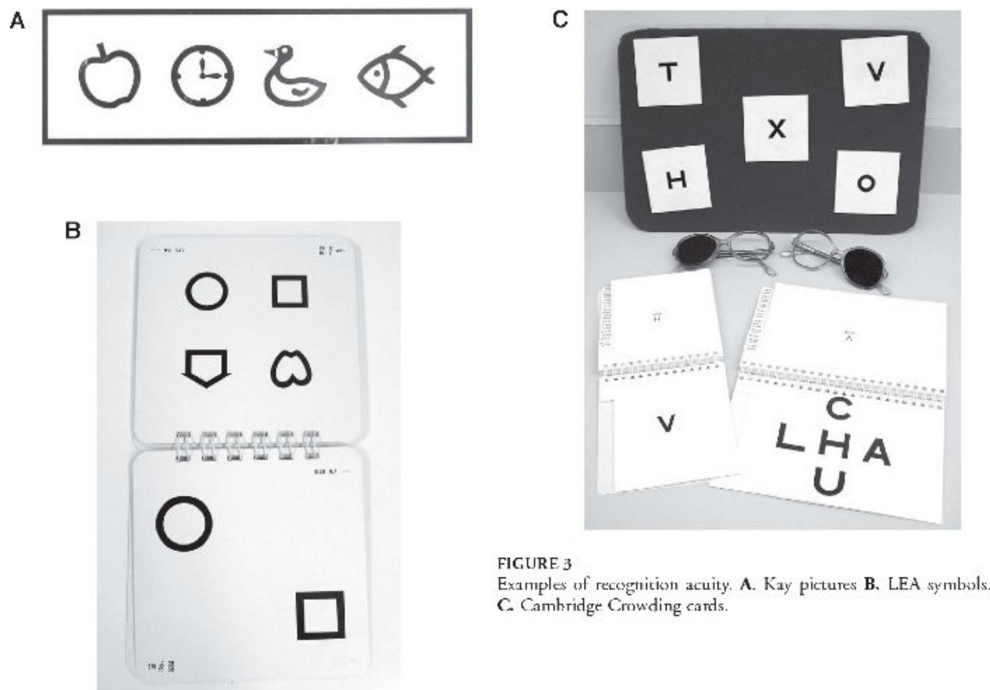

FIGURE 3
Examples of recognition acuity. A. Kay pictures B. LEA symbols.
C. Cambridge Crowding cards.

Glasgow Acuity Card. The picture is adapted from: http://bmj-bjo.highwire.org/content/81/6/465.full

Appendices: (2) Recognition thresholds plotted as a function of separation in letter widths. The top, middle and bottom panel represents the data for four, three and two amblyopic subjects respectively. Each datum represents the mean low contrast recognition threshold for each separation condition. The datum points in blue and red represents the mean thresholds for the non-amblyopic eyes and amblyopic eyes respectively. The error bars represents ±1 SE. (3) Normalised recognition thresholds plotted as a function of separation in letter widths. The top, middle and bottom panel represents the data for four, three and two amblyopic subjects respectively. Each datum represents the mean low contrast recognition thresholds normalised against the isolated letter threshold (threshold value at each separation - isolated letter threshold value). The datum points in blue and red represents the non-amblyopic eyes and amblyopic eyes respectively. The error bars represents ±1 SE.

Appendix 2:

Appendix 3:

Appendix 4: The percentage of substitution and random errors and the difference between the two are shown for all the separation conditions and for normal, non-amblyopic and amblyopic eyes. A negative sign indicates greater proportion of substitution errors than the random errors.

Subjects	Separations (letter width)	percentage of substitution error	percentage of random error	Random error - Substitution error
Normal eyes				
VV	>1.0	6.35	44.05	37.70
	1.0	9.92	37.30	27.38
	0.2	10.12	35.52	25.40
	abutting	12.50	32.14	19.64
JS	>1.0	13.10	36.51	23.41
	1.0	14.68	31.35	16.67
	0.2	23.81	28.17	4.37
	abutting	16.40	24.87	8.47
EO	>1.0			
	1.0	13.29	44.05	30.75
	0.2	17.46	31.35	13.89
	abutting	14.29	38.10	23.81

Subjects	Separations (letter width)	percentage of substitution error	percentage of random error	Random error - Substitution error
Non-amblyopic eyes				
SR	>1.0	10.32	34.13	23.81
	1.0	6.35	34.92	28.57
	0.2	12.70	36.90	24.21
	abutting	6.35	34.92	28.57
AB	>1.0	9.21	38.41	29.21
	1.0	15.08	28.77	13.69
	0.2	12.70	28.57	15.87
	abutting	15.87	27.58	11.71
RC	>1.0	9.84	35.87	26.03
	1.0	20.81	35.35	14.55
	0.2	19.05	31.35	12.30
	abutting	18.18	27.07	8.89
VS	>1.0	6.75	38.49	31.75
	1.0	18.12	34.78	16.67
	0.2	20.18	31.29	11.11
	abutting	16.11	29.44	13.33

Amblyopic eyes	Separations (letter width)	percentage of substitution error	percentage of random error	Random error - Substitution error
SR	>1.0	19.84	25.40	5.56
	1.0	32.54	17.46	-15.08
	0.2	23.41	16.67	-6.75
	abutting	25.40	17.46	-7.94
AB	>1.0	9.52	36.51	26.98
	1.0	24.21	22.22	-1.98
	0.2	23.61	18.25	-5.36
	abutting	19.84	24.21	4.37
RC	>1.0	8.73	34.92	26.19
	1.0	11.11	32.14	21.03
	0.2	16.27	26.19	9.92
	abutting	15.08	34.92	19.84
VS	>1.0	15.48	35.71	20.24
	1.0	16.40	36.51	20.11
	0.2	18.80	29.06	10.26
	abutting	15.48	28.57	13.10

Appendix 5: Depicts the letter confusion pairs for SG isolated, SGRL thresholds and SGCI thresholds for abutting, 0.2, 1.0 and greater than 1.0 letter width separations for normal, non-amblyopic and amblyopic eyes.

SG isolated letter thresholds				SGRL thresholds			SGCI thresholds		
Normal eyes	NAE	AE	Separation	Normal eyes	NAE	AE	Normal eyes	NAE	AE
H-O	A-X	U-H	Abutting	H-T, X-V	H-T, T-H	A-U, H-T, T-H	H-T, X-A	X-V	O-X
U-H	T-V		0.2	H-T, T-H	H-T, T-H	H-T, T-H	X-A		
X-A	U-H		1				H-U,X-A		
	U-O		>1.0				A-X, U-H, V-T	A-X,H-U	

Appendix 6: Supporting conference presentations

- Varikuti V, Further insights into letter crowding. Anglia Ruskin University, Departmental research Seminar, October 2010
- Varikuti V, Visual acuity and crowding. Anglia Ruskin University Postgraduate research conference, Chelmsford, May 2009.
- Varikuti V, Siderov J & Waugh, S J. Contour interaction for high and low contrast repeat letter charts. Presented at Asia – ARVO, Hyderabad, India. January 2009.
- Varikuti V, Visual crowding: contour interaction and contrast. Anglia Ruskin University, Departmental research Seminar, November 2008.
- Siderov J, Varikuti V, & Waugh S J. Contour interaction in repeat acuity charts. Presented at American Academy of Optometry Annual Meeting, Anaheim, USA, and October 2008.
- Varikuti V, The importance of letter spacing in vision charts. Anglia Ruskin University Postgraduate Research Conference, Cambridge, April 2008.
- Varikuti V, Visual crowding and contour interaction. Anglia Ruskin University, Departmental research Seminar, May 2007.