Vision Research 121 (2016) 31–38

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Crowding and visual acuity measured in adults using paediatric test letters, pictures and symbols

Sarah J.H. Lalor, Monika A. Formankiewicz, Sarah J. Waugh *

Anglia Vision Research, Department of Vision and Hearing Sciences, Anglia Ruskin University, East Rd, Cambridge CB1 1PT, United Kingdom

ARTICLE INFO

Article history:
Received 7 September 2015
Received in revised form 11 January 2016
Accepted 19 January 2016

Keywords:
Visual acuity
Paediatric visual acuity charts
Crowding
Symbol and picture optotypes
Psychometric function slopes

ABSTRACT

Crowding refers to the degradation of visual acuity for target optotypes with, versus without, surrounding features. Crowding is important clinically, however the effect of target-flanker spacing on acuity for symbols and pictures, compared to letters, has not been investigated. Five adults with corrected-to-normal vision had visual acuity measured for modified single target versions of Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding Cards, tests. Single optotypes were presented in isolation and with surrounding features placed 0–5 stroke-widths away. Visual acuity measured with Kay Picture optotypes is 0.13–0.19 logMAR better than for other test optotypes and varies significantly across picture. The magnitude of crowding is strongest when the surrounding features abut, or are placed 1 stroke-width away from the target optotype. The slope of the psychometric function is steeper in the region just beyond maximum crowding. Crowding is strongest and the psychometric function steepest, with the Cambridge Crowding Cards arrangement, than when any single optotype is surrounded by a box. Estimates of crowding extent are less variable across test when expressed in units of stroke-width, than optotype-width. Crowding for single target presentations of letters, symbols and pictures used in paediatric visual acuity tests can be maximised and made more sensitive to change in visual acuity, by careful selection of optotype, by surrounding the target with similar flankers, and by using a closer target-flanker separation than half an optotype-width.

1. Introduction

Visual acuity is routinely measured by clinicians as part of ocular health and visual function assessment, and during pre-school vision screenings. Detection of amblyopia, a developmental vision disorder affecting approximately 3.5% of adults (Attebo et al., 1998), is a key reason for pre-school vision screening (Bodack, Chung, & Krumholtz, 2010; Friendly, 1978; Kemper, Keating, Jackson, & Levin, 2005; Schlenker, Christakis, & Braga-Mele, 2010; Schmucker et al., 2009; U.S. Preventive Services Task Force, 2004) as treatment is more likely to be successful if initiated early in life (Flynn, Schiffman, Feuer, & Corona, 1998; Flynn et al., 1999). Inter-ocular visual acuity differences are a key component of amblyopia diagnosis and monitoring of treatment outcomes (Attebo et al., 1998; Flom & Neumaier, 1966; Flynn et al., 1998, 1999; Holmes & Clarke, 2006; Simons, 2005). A number of visual acuity tests are available for the testing of pre-literate children, as well as in adults who cannot communicate using the Latin alphabet. These tests vary in the optotypes chosen, i.e., letters, symbols or pictures, their arrangement on the test chart, i.e., a single optotype, a line of optotypes, or the presence of other features around the target optotype such as other letters, bars or a box (Anstice & Thompson, 2014; Fern & Manny, 1986). There are also differences in the discriminability of optotypes used in these charts (Candy, Mishoulam, Nosofsky, & Dobson, 2011).

Visual acuity for a target optotype measured with surrounding features is worse than that measured when isolated (Flom, Weymouth, & Kahneman, 1963; Formankiewicz & Waugh, 2013; Jacobs, 1979; Leat, Li, & Epp, 1999). This negative spatial interaction effect on target resolvability is generally referred to as "crowding" and may be greater in amblyopes than in individuals with normal vision (Hess, Dakin, Tewfik, & Brown, 2001; Levi, Hariharan, & Klein, 2002; Mayer & Gross, 1990; Morad, Werker, & Nemet, 1999; but see Flom, Weymouth, & Kahneman, 1963; Stuart & Burian, 1962). Contour interaction was proposed to be a sub-component of crowding (along with attention and eye movements) by Flom et al. (1963) and refers to the detrimental effects of bars (or contours) that surround the target. In crowding, detrimental effects are produced by surrounding the target with more complex features similar to the target itself, such as other letters. Alternatively, contour interaction and crowding have been

* Corresponding author.
E-mail address: sarah.waugh@anglia.ac.uk (S.J. Waugh).

http://dx.doi.org/10.1016/j.visres.2016.01.007
0042-6989/© 2016 The Authors. Published by Elsevier Ltd.

proposed to be distinct entities (Pelli, Palomares, & Majaj, 2004). However clinically, contours, boxes, and neighbouring optotypes have been incorporated into visual acuity charts to introduce "crowding" effects (Atkinson, Anker, Evans, Hall, & Pimm-Smith, 1988; McGraw & Winn, 1993; McGraw, Winn, Gray, & Elliot, 2000; Schlenker et al., 2010; Simmers, Gray, & Spowart, 1997) to improve the sensitivity of visual acuity measurement in detecting amblyopia.

The position of crowding features on commercially available acuity charts is based primarily on the findings of Flom et al. (1963). Flom et al. investigated contour interaction using an orientation discrimination task with a rotated C flanked by bars. They reported that performance is maximally degraded when bars are placed at an edge-to-edge distance of 0.4 letter (or 2 stroke) widths. Crowding features, such as other letters, bars or a box, on children's visual acuity charts are generally placed 0.5 optotype-widths away from the target letter or line of symbols, pictures or letters (Atkinson et al., 1988; Holmes, Beck, Repka, et al., 2001; Jones, Westall, Averbeck, & Abdolell, 2003; McGraw & Winn, 1993; Vision in Preschoolers Study Group, 2005). A separation of 1 optotype width has been used on the Sonksen chart (Salt, Wade, Proffitt, Heavens, & Sonksen, 2007), which follows the design of the Bailey–Lovie chart (Bailey & Lovie, 1976).

Acuity tests designed for young children (and adults who cannot communicate using the Latin alphabet) normally require recognition or matching of letter or picture/symbol optotypes, which are more complex than a Landolt C. Recent research has indicated that crowding for letter optotypes would be enhanced if crowding features were placed closer to the optotypes than in currently available charts (Formankiewicz & Waugh, 2013; Song, Levi, & Pelli, 2014). Crowded tests are recommended for children's vision screening programs (Cotter, Cyert, Miller, Quinn, & National Expert Panel to the National Center for Children's Vision and Eye Health, 2015; Solebo & Rahi, 2013); specifically isolated optotypes (HOTV or Lea) with crowding bars are considered "best-practice" for children less than 6 years of age (Cotter et al., 2015). The effects of varying the position of crowding features on visual acuity measured with single picture and symbol optotypes have not yet been investigated.

In the present study, crowding for single target presentations of optotypes from four visual acuity charts, i.e., Kay Pictures, Lea Symbols, HOTV and Cambridge Crowding Cards, is compared in adult observers. Kay Pictures (Kay, 1983) are commonly used in the UK and Europe (Anstice & Thompson, 2014; Beirne, McIlreavy, & Zlatkova, 2008; Little, Molloy, & Saunders, 2012; Shah, Laidlaw, Rashid, & Hysi, 2012; Williams et al., 2015) Each optotype-width (or height) contains 10 stroke-widths to enable the more intricate pictures to be recognizable by young children, whilst having the same stroke-width as Snellen letters (Kay, 1983). Lea Symbols, recently recommended by a National Expert Panel (USA) to be used for vision screening in young children (Cotter et al., 2015), have sizes scaled to provide visual acuities similar to the Landolt C and contain, on average, 7 stroke-widths per optotype in order to keep the total amount of blackness closely equal (http://www.lea-test.fi). HOTV optotypes follow the Snellen letter design and contain 5 stroke-widths per optotype (Snellen 1862 cited by Bennett, 1965; British Standards Institution., 2003; Sheridan & Gardiner, 1970); Cambridge Crowding Cards use HOTVX as target letters, and other Sheridan-Gardiner letters to surround the target letter (Atkinson et al., 1988; Sheridan & Gardiner, 1970). The position of crowding features in visual acuity tests is normally specified in terms of target optotype size (Holmes et al., 2001; Jones et al., 2003; McGraw & Winn, 1993), however visual acuity is based on the optotype detail, or stroke-width. In this study we examine whether optotype- or stroke-width provides a more consistent unit for specifying crowding position across picture, symbol and letter acuity tests.

The purpose of this study is therefore (1) to compare visual acuity measured using single target presentations of optotypes from different visual acuity tests, (2) to determine the optimum positioning of crowding features on single target presentations, and (3) to determine which units (optotype- or stroke-widths) are best for specifying the position of crowding features. Whilst it would be beneficial to investigate crowding for these optotypes in young children, with adult participants a range of flanker positions and target types can be tested using rigorous psychophysical methods. The results will have direct applicability to adults who cannot communicate using the Latin alphabet, and will also be helpful in selecting only a few conditions to be tested on young children. The implications of our results obtained with adult participants, for the testing of children, will also be discussed.

2. Method

2.1. Apparatus

The stimuli were generated using a custom-written Matlab program (MathWorks™) on a Dell Precision T3400 computer driving a Cambridge Research Systems ViSaGe (Visual Stimulus Generator), a system which has integrated support for gamma correction. The stimuli were displayed on a Mitsubishi Diamond Pro 2070^{SB} CRT computer monitor. The screen resolution was 1104 × 828 and the frame rate was 120 Hz. The CRT display was calibrated and gamma-corrected using an OptiCal photometer to correct each gun's non-linearity. The monitor was switched on at least 60 min before data collection began to ensure the luminance output was stable.

2.2. Stimuli

Optotypes used in this study were derived from four preliterate visual acuity charts: Kay Picture Test (Kay Pictures Ltd, Tring UK) (Kay, 1983), Lea Symbols (Good-Lite, Illionois, USA) (Hyvarinen, Nasanen, & Laurinen, 1980), HOTV (Precision Vision, Illionois, USA) (Lippmann, 1971) and Cambridge Crowding Cards (Clement Clarke, Harlow, UK) (Atkinson et al., 1988). Optotypes were scanned from the original charts, converted to matrices and scaled for the different sizes required. They were displayed as black images (0.6 cd/m^2) on a white background (102 cd/m^2), at a contrast of 99.4%.

The original charts comprise different numbers of optotypes. To equalise the guess rate (at 1 in 4) across tests, target optotypes had to be removed from the Cambridge Crowding Cards and Kay Picture Test as the Lea Symbols and HOTV charts use four optotypes. The Cambridge Crowding Cards use five target optotypes (H, O, T, V and X) as standard, four being the same as in the HOTV chart and so, for the purposes of this study, the X was not used. The Kay Picture Test has eight optotypes (apple, boot, clock, cup, duck, fish, house and truck) and so for the current study, a preliminary experiment was conducted to choose four pictures that gave equivalent visual acuities and crowding effects.

Optotypes were displayed individually without crowding features (referred to as the isolated condition), and with crowding features at a separation of 0 (abutting), 1, 2, 3, 4 and 5 stroke-widths away. Separation is defined as the distance between the optotype edge and the inner edge of the crowding feature(s). In the main experiment, for the Kay Pictures, Lea Symbols and HOTV tests, the crowding feature was a box, which surrounded a single target optotype (in commercially available charts, a box is placed around a group of 4 or 5 optotypes). For the Cambridge Crowding Cards, the single target optotype was surrounded by four letters (A, C, L and U) in random configurations. Target optotypes and examples of crowded displays are shown in Fig. 1.

In an additional control experiment, four bars (above, below, to the right and to the left of the optotype) rather than a box were used as crowding features. Crowding is reduced when flankers can be grouped into a single object compared to using separate multiple objects (Herzog, Sayim, Chicherov, & Manassi, 2015; Levi & Carney, 2009; Malania, Herzog, & Westheimer, 2007; Manassi, Sayim, & Herzog, 2012). Therefore, using a box in the main experiment as a flanking feature (i.e. a 'grouped' object) could have potentially lowered the crowding effects compared to when four bars are used.

2.3. Participants

Five adult participants who regularly use the Latin alphabet (mean age: 23.8 years, range 22–25 years) took part in the main experiment. Four participants completed the pilot experiment and two participants completed the grouping control. One participant (SL) was one of the authors and the other participants were naïve as to the aims of the experiment. All participants wore their full spectacle correction (best vision sphere of −2.25 D to +0.75 D) and had a visual acuity of 6/5 or better in each eye. Stereoacuity was 60 arcsec or better, measured with the Dutch Organization for Applied Scientific Research (TNO) stereo test (Lameris Ootech, Ede, The Netherlands). It was important to ensure that participants had normal binocular vision, as crowding effects can be different in individuals who have disrupted binocularity. These experiments were carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki, 1975) and approval of the experimental protocol was obtained from the appropriate Anglia Ruskin University Human Research Ethics Committee. All participants provided written informed consent before the experiments were conducted and after the nature and consequences of the study were explained.

2.4. Procedure

2.4.1. Pilot experiment

A pilot experiment was carried out to choose four out of the eight optotypes used in the commercially available Kay Picture Test. A method of constant stimuli with an 8-alternative forced-choice (8AFC) procedure was used to collect the data. In each experimental run, 100 trials were shown, in which optotypes across a range of seven sizes, separated by approximately 0.1 logMAR were randomly presented. The sizes were chosen so that the correct responses would range from guess rate (12.5%) to 100%. Testing was monocular with the other eye occluded with a black patch. Participants viewed the screen from a distance of 9 to 11.5 m and had to indicate verbally or by pressing an appropriate button, which of the eight optotypes had been displayed: apple, boot, clock, cup, duck, fish, house or truck. The viewing distance had to be adjusted for individual observers to allow a range of sizes to be displayed that spanned performance levels from guess rate to 100%.

The target optotype was displayed individually without any crowding features and flanked by a box placed at separation of 0 (abutting), 1 and 5 stroke-widths away from the target. Only one target-flanker separation was used in each experimental run and runs were counterbalanced across crowding separation. In each experimental run, data for the individual optotypes were kept separately, so that visual acuity for each optotype could be determined. Data from 16 (for 2 participants) or 32 (for 2 participants) experimental runs per crowding condition were averaged (allowing for 200 or 400 trials to be accumulated for each of the 8 original optotypes). Each participant also completed practice sessions before data collection began to ensure they were familiar with the task and the optotypes.

2.4.2. Main experiment

Data in the main experiment were collected using procedures similar to those described for the pilot study. Therefore, only differences are outlined now.

Each test used in the main experiment (HOTV, modified Kay Pictures, Lea Symbols, modified Cambridge Crowding arrangement) had four optotypes, so a four-alternative forced-choice (4AFC) procedure was used to collect the data. The target optotype was displayed individually without any crowding features and flanked by a box (or bars in the control) placed at separation of 0 (abutting), 1, 2, 3, 4, and 5 stroke-widths away from the target. The tests were done in different orders by different participants to counterbalance the effects of fatigue and familiarity. Data were averaged across all optotypes within each test for 4–6 experimental runs (i.e., 400–600 trials).

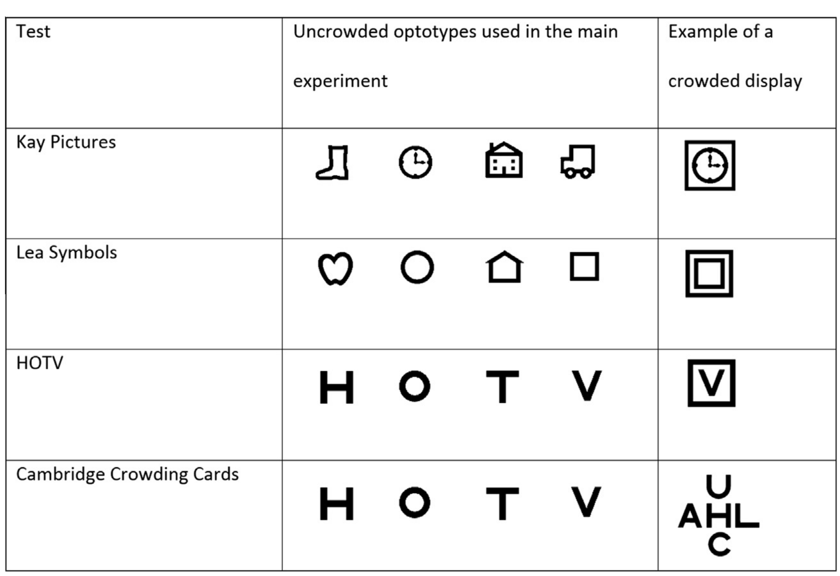

Fig. 1. The target optotypes used and examples of crowded displays with crowding features placed 1 stroke-width away from the target.

2.5. Analysis

Visual acuity thresholds and slopes were estimated from Weibull function fits to psychometric performance data (Weibull, 1951), as has previously been applied in letter acuity studies (Alexander, Xie, & Derlacki, 1997; Pelli, Robson, & Wilkins, 1988):

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

where g is the guess rate (12.5% for the 8-AFC pilot experiment and 25% for the 4-AFC main experiment), β is the slope of the psychometric function, s is the target size in logMAR and th is the estimated threshold in logMAR (which is equivalent to 67.8% correct performance for the pilot experiment and 72.4% correct performance for the main experiment).

The magnitude of crowding was assessed by comparing visual acuity measured in the presence of crowding features to the visual acuity measured for an isolated, unflanked optotype. In the main experiment, peak crowding is the largest detrimental effect of the surrounding features on visual acuity. Extent of crowding was defined as the smallest target-flanker separation at which the flanked acuity was not significantly different statistically, from unflanked acuity.

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

3. Results

3.1. Pilot experiment

Visual acuities measured with each of the Kay picture optotypes are shown in Fig. 2a and the magnitude of crowding, i.e., the difference between visual acuity with flanking features and without, is plotted in Fig. 2b.

Visual acuities obtained with an isolated optotype ranged from -0.36 ± 0.056 for the ‘duck’ to -0.13 ± 0.024 for the ‘apple’. A repeated measures ANOVA was used to analyse the effects of optotype and position of flanking features (including the isolated condition) on visual acuity. It revealed a statistically significant main effect of optotype used [$F(2.68, 8.04) = 8.74$, $p = 0.007$] and position of the crowding features [$F(2, 6) = 22.23$, $p = 0.002$]. The lowest (best) visual acuity was obtained for the ‘duck’ optotype, which was significantly better than all other optotypes [post hoc, $p < 0.05$] except ‘boot’ and ‘fish’. Crowding was evident when the box was placed 1 stroke-width away from the optotype as overall, visual acuity was significantly worse than with the isolated optotype [post hoc, $p < 0.05$]. There was no significant difference in visual acuity between the isolated optotype and when the box was placed at 5 stroke-widths away [post hoc, $p > 0.05$].

Fig. 2b shows that the effect of the flanking box is different for the different optotypes when the box is placed 1 stroke-width away from the optotype. In fact the ‘apple’, ‘duck’ and ‘fish’ optotypes did not show any crowding (when flankers were placed 1 stroke-width away).

The ‘fish’ and ‘cup’ optotypes are not designed on a square grid; the ‘fish’ being wider than taller and the ‘cup’, taller than wider. A square box around would result in different separations between the optotype edges and the box vertically and horizontally. A rectangular box on the other hand could be used as a shape cue to help in the recognition of the optotype. The ‘fish’ optotype also showed minimal crowding when flankers were placed at a separation of 1 stroke-width. The ‘fish’ and the ‘cup’ were therefore not used in the main experiment.

Based on the results, the four Kay picture optotypes used in the main experiment were: ‘boot’, ‘clock’, ‘house’ and ‘truck’. There is no statistical difference in the visual acuity or magnitude of crowding obtained with the four chosen optotypes.

The differences in visual acuity obtained for the individual optotypes used on the Kay Pictures charts suggest that the legibility of these optotypes varies. A variation in legibility of optotypes in other children’s visual acuity tests has also been reported (Candy et al., 2011). Differences in optotype legibility mean that the measured visual acuity could be affected by the legibilities of the optotypes chosen for a particular level of visual acuity (or line on a letter chart) and not only, as intended, by the resolution ability of the eye.

The result that the magnitude of crowding is different for different optotypes also has clinical implications for the measurement of visual acuity on crowded charts as again that may be affected by the selection of optotypes on a particular line or acuity level.

3.2. Main experiment

3.2.1. Visual acuity

Acuities for the different visual acuity tests (each now with only 4 optotypes) and target-flanker separations, averaged across 5 participants, are shown in Fig. 3a. Visual acuities were affected by the test used, presence of crowding features and their distance away from the optotype. A 4 (test) $\times$ 7 (target-flanker separation, including the isolated presentation) repeated measures ANOVA revealed a statistically significant interaction between test type and flanker position [$F(13.05, 52.20) = 6.98$, $p < 0.001$]. Visual acuities at all target-flanker separations were lower (better) with the Kay Pictures than with the HOTV test, Lea Symbols and Cambridge Crowding Cards [$p < 0.05$ for all separations and tests]. Averaged across

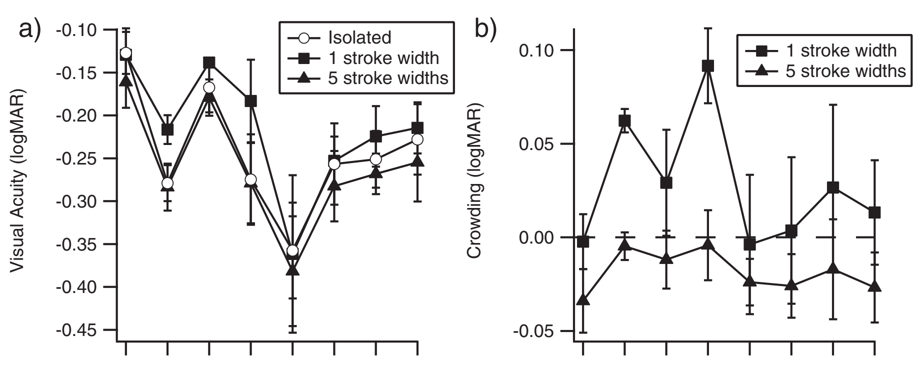

Fig. 2. Results of the pilot experiment averaged across participants showing (a) visual acuities and (b) magnitude of crowding, for eight Kay Picture optotypes presented without flankers and when the flankers were placed at 1 and 5 stroke-widths away. The dashed line shows the level of no crowding. Error bars indicate ±1 SEM.

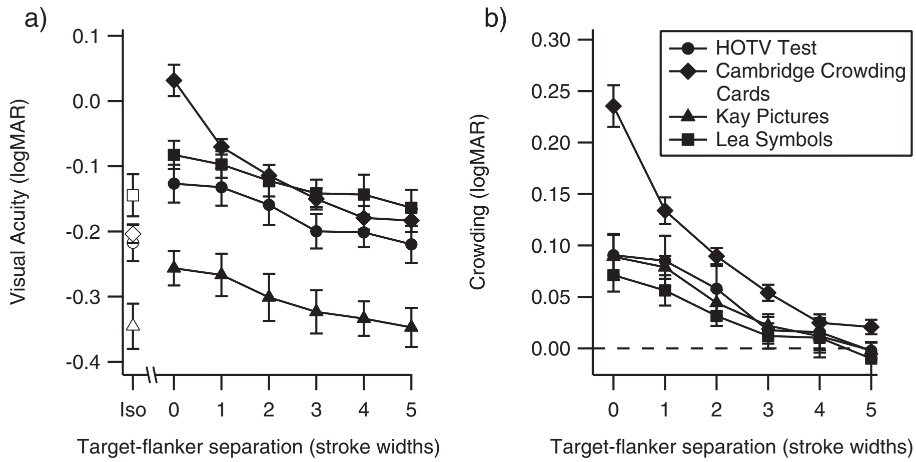

Fig. 3. (a) Visual acuities averaged across participants for Kay Pictures, Lea Symbols, HOTV test and Cambridge Crowding Cards, presented without flankers (Iso) and when the flankers were placed at 0, 1, 2, 3, 4 and 5 stroke-widths away. (b) Magnitude of crowding averaged across participants for the Kay Pictures, Lea Symbols, HOTV test and Cambridge Crowding Cards. The dashed black line shows the level of no crowding. SE indicates ±1 SEM.

separation, visual acuities measured with the Kay Pictures were 0.131 ± 0.008, 0.183 ± 0.007 and 0.186 ± 0.012 logMAR better than with the HOTV test, Lea Symbols and Cambridge Crowding Cards, respectively. For an isolated optotype and when crowding features were 3 or more stroke-widths away from the optotype, visual acuities were highest (worst) with the Lea Symbols. When the crowding features were two or less stroke-widths away from the optotype, visual acuities were worst with the Cambridge Crowding Cards. Statistically, Cambridge Crowding Cards resulted in significantly higher (worse) visual acuities than all other tests only when the flankers were abutting the target [$p < 0.05$ for all tests].

3.2.2. Crowding

The magnitude of crowding, i.e. the difference between flanked and isolated visual acuity as function of separation between the flankers and the optotype is shown in Fig. 3b. The magnitude of crowding was greater for the Cambridge Crowding Cards than the magnitude of contour interaction seen with the other tests used, and for all tests, it decreased as the flankers moved from abutting to 5 stroke-widths away from the target. The data were analysed using a 4 (test) × 6 (target-flanker separation) repeated measures ANOVA. The effect of test used on the magnitude of crowding was dependant on the separation between the flankers and the optotype, as indicated by a statistically significant interaction [$F(7.64, 30.55) = 6.74$, $p < 0.001$]. The magnitude of crowding was affected by the test used when the flankers were 0, 1 and 2 [$p < 0.05$] stroke-widths away from the target. When the flankers were abutting the target, crowding was significantly greater with the Cambridge Crowding Cards than with the Kay Pictures, Lea Symbols and the HOTV test [$p < 0.05$ for all]. Crowding was also greater with the Cambridge Crowding Cards than with the Lea Symbols at a separation of 1 and 2 stroke-widths [post hoc; $p < 0.05$]. The magnitude of crowding was not affected by the test used at separations of 3 [$F(3,12) = 3.03$, $p = 0.069$], 4 [$F(2.96, 11.82) = 0.25$, $p = 0.85$] and 5 stroke-widths [$F(3,12) = 1.97$, $p = 0.17$].

3.2.3. Peak magnitude of crowding

For individual observers, the peak magnitude of crowding occurred when the target was either abutting or 1 stroke-width away from the optotype. The peak magnitude was affected by the chart used [$F(3,12) = 18.60$, $p < 0.001$]. Post-hoc analysis indicated that crowding by letters, i.e., the effect seen with the Cambridge Crowding Cards was significantly greater at 0.24 ± 0.02 logMAR than contour interaction with the Lea Symbols at 0.07 ± 0.02 logMAR, Kay Pictures at 0.10 ± 0.01 logMAR and HOTV test at 0.10 ± 0.02 logMAR [$p < 0.05$ for all tests].

3.2.4. Extent of crowding

The extent of crowding was defined as the closest target-flanker separation at which flanked acuity was not significantly different from isolated acuity using post hoc Tukey HSD test comparisons. Extents were obtained in stroke-widths and then converted to optotype-widths as separations between optotype and flanking features on the commercially available charts are often specified using this unit. To achieve this, the extent in stroke-widths was divided by the number of strokes in each optotype, i.e., 5 for the letter the HOTV test and Cambridge Crowding Cards, 10 for Kay Pictures and 7 (averaged across optotypes) for Lea Symbols. Extents in stroke-widths were also converted to arcmin as this has recently been suggested as an appropriate unit for specifying the extent of crowding (Bedell et al., 2013; Danilova & Bondarko, 2007; Siderov, Waugh, & Bedell, 2013) This was done by multiplying the extent in stroke-widths for each test by the visual acuity obtained. The extents are provided in Table 1.

On average, the extent of crowding was 2.5 ± 0.65 stroke-widths, 0.44 ± 0.16 optotypes widths or 1.60 ± 0.43 arcmin. The variance in extent across different tests is 30% smaller when expressed in stroke-widths and arcmin than optotype-widths.

3.2.5. Slope of the psychometric function

Psychometric function slopes for the different tests and target-flanker separations are shown Fig. 4. Slopes were significantly affected by target-flanker separation [$F(3,12) = 7.66$, $p = 0.004$]

Table 1
Extent of crowding in stroke-widths, optotype-widths and arcmin.

	Extent in stoke widths	Extent in optotype-widths	Extent in arcmin ± SE
Cambridge Crowding Cards	4	0.8	2.65 ± 0.11
HOTV test	3	0.6	1.91 ± 0.12
Kay Picture Test	2	0.2	1.01 ± 0.092
Lea Symbols*	1	0.14	0.80 ± 0.037
Average ± SE	2.5 ± 0.65	0.44 ± 0.16	1.60 ± 0.43
Variance (%) (SE/average)	26%	36%	27%

* Two of the Lea Symbols vary slightly in height and width, based on direct measurement.

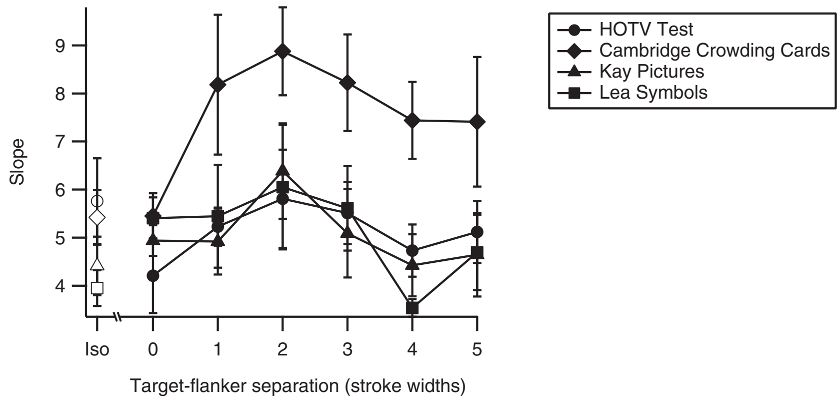

Fig. 4. Slopes of the psychometric function averaged across participants for the Kay Pictures, Lea Symbols, HOTV test and Cambridge Crowding Cards, presented without flankers (Iso) and when the flankers were placed at 0, 1, 2, 3, 4 and 5 stroke-widths away from the target. Error bars indicate ±1 SEM.

and by test [$F(4.11,16.42) = 3.14$, $p = 0.04$]. Slopes were significantly different, and steeper than for the isolated condition, at a separation of 2 stroke-widths only [post hoc; $p = 0.03$]. Slopes for the Cambridge Crowding Cards were significantly steeper than those for the other three tests [post hoc; $p < 0.05$ for all].

3.2.6. Box vs Bars as flanking features

Crowding functions, i.e. magnitude of contour interaction as a function of separation between target and flanker, for the picture (average of Kay Pictures, Lea Symbols) and letter optotypes, flanked by four bars and a box, are shown in Fig. 5. There was no statistical difference between the results obtained for two observers [$F(1,1) = 2.09$, $p = 0.39$]. The pattern of results in the figure suggests that bars at the position of peak crowding may be more effective than a box, at least for letter targets. However, a more in-depth investigation on greater numbers of participants in future is required to test this.

4. Discussion

4.1. Visual acuity

Visual acuity measured is affected by the target optotype used (Lea, Kay, HOTV and Cambridge Crowded) and placement of crowding features. The results of the present study using single presentations of 4 optotypes for each test, indicate that visual acuity for Kay Pictures is 1–2 lines better than when measured using HOTV letters, Lea Symbols or a Cambridge Crowded arrangement of letters. This result is in agreement with previous studies in which visual acuity was measured with the full set of Kay Pictures, and other tests in their commercially available configurations (Formankiewicz & Waugh, 2013; Jones et al., 2003; Shah et al., 2012).

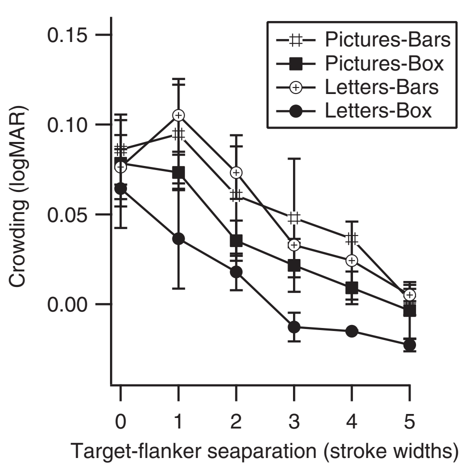

Fig. 5. Magnitude of crowding averaged across two participants for (a) picture (average of Kay Pictures and Lea Symbols) and (b) letter (HOTV) optotypes, flanked by bars and a box placed 0, 1, 2, 3, 4 and 5 stroke-widths away from the target. SE indicates ±1 SEM.

4.2. Crowding

Visual acuity tests designed primarily for use on young children, but also for adults not familiar with the Latin alphabet, often contain crowding features to aid the detection of amblyopia (Atkinson et al., 1988; McGraw & Winn, 1993; McGraw et al., 2000; Schlenker et al., 2010; Simmers, Gray, & Spowart, 1997). Our results indicate that the reduction of visual acuity when an optotype is surrounded by a box or bars, is similar for letter and picture or symbol optotypes. When letters are surrounded by other letters, the crowding effect increases.

Recently, it has been suggested that to enhance the effects of crowding, flankers on letter visual acuity charts designed to screen for amblyopia should be placed at closer separations than the 0.5 optotype-width used on most charts (Formankiewicz & Waugh, 2013; Song et al., 2014). Results of the current study extend this finding to single target presentations of letters, pictures or symbols.

The position of flankers on currently available acuity charts is specified as separation of nearest edges of target and flankers in proportion to target optotype size (Atkinson et al., 1988; Holmes et al., 2001; Jones et al., 2003; McGraw & Winn, 1993). This metric produces crowding extents that are more variable than when units of stroke-width (or minutes of arc) are used. When specified in optotype-widths, a placement of 0.5 optotype-widths corresponds to 2.5 stroke-widths for the HOTV test and Cambridge Crowding Cards, 5 stroke-widths for the Kay Pictures and 3.5 stroke-widths (on average) for the Lea Symbols. This variability makes it difficult to reliably compare crowded visual acuity results across chart. The results of the current study suggest that use of stroke-width, rather than optotype-width to specify the position of flanking features, leads to more consistent crowding effects across chart. In line with the results of others (Bedell et al., 2013; Danilova & Bondarko, 2007; Siderov et al., 2013) use of units of arcmin reveal a small extent of foveal crowding (0.7–2.9′), with consistency across chart similar to that found with units of stroke-width.

When the target was surrounded by a box, the peak magnitude of crowding was similar for picture/symbol and letter optotypes, i.e., Kay Pictures, Lea Symbols and HOTV test, at 0.09 ± 0.01 logMAR (1 line on a letter chart) on average. It was greater when a target letter was surrounded by other letters, such as in the Cambridge Crowding Cards, at 0.24 ± 0.02 logMAR (~2.5 lines on a letter chart). Although, not statistically significant, the Cambridge Crowding Cards also resulted in greater levels of crowding at other target flanker separations, especially for close target-flanker separations. This increase in crowding can be attributed to the greater similarity of the flanking letters to the target letter (Bernard & Chung, 2011; Kooi, Toet, Tripathy, & Levi, 1994), and/or the greater 'complexity' of the letter flankers than the box (Bernard & Chung, 2011). In line with other recent papers, tests that aim to screen for amblyopia should incorporate letter flankers to increase the effect of crowding (Formankiewicz & Waugh, 2013; Song et al., 2014). However, a target letter surrounded by other letters may be too complicated for some young children. The results of this paper show that simple contours placed around a single target letter, symbol or picture (placed outside the resolution limit of the eye so not abutting the target) also do produce significant degradative effects on visual acuity.

4.3. Slopes of psychometric function

The slope of the psychometric function for a visual acuity chart indicates the sensitivity of that chart to changes in acuity. Our assessment of the underlying psychometric function found slopes to be steeper under crowded conditions than for an isolated target, especially when the flankers were 2 stroke-widths away from the target. It is interesting to note that steepest slopes do not coincide exactly with the point of maximum crowding, i.e., abutting or 1 stroke-width separation, but occur for slightly further flanker separations. Psychometric function slopes are steeper for the Cambridge Crowding Cards arrangement than for the other three tests.

4.4. Implications of the results for the measurement of visual acuity in children

The current study used single presentations of letter, picture and symbol optotypes designed primarily for use in children, but the experiments were carried out on adult participants due to the number of conditions involved, an approach also taken by other researchers (Candy et al., 2011; Little et al., 2012; Song et al., 2014). Although the results are relevant to adult visual systems, they are potentially not relevant to developing ones. Visual acuity is worse in young children than in adults, however the relationship between visual acuities obtained across different charts has been found to be similar for children and adults (Candy et al., 2011; Mercer, Drover, Penney, Courage, & Adams, 2013). Therefore some results of visual acuity testing obtained with adults, which may require lengthy psychophysical procedures and numerous testing conditions, may be extrapolated to children, for whom the charts were primarily designed.

It has been reported that crowding in children is more extensive and of greater magnitude than in adults (Atkinson, Pimm-Smith, Evans, Harding, & Braddick, 1986; Atkinson et al., 1988; Jeon, Hamid, Maurer, & Lewis, 2010; Masgoret, Asper, Alexander, & Suttle, 2011; Norgett & Siderov, 2014). Therefore if adults in our study demonstrate crowding, children also ought to, although they may respond differently to different crowding/grouping features than adults (Atkinson et al., 1986; Kovacs, 2000; Scherf, Behrmann, Kimchi, & Luna, 2009). For both children and adults, visual acuity for letter targets improves systematically as the flankers move away from the target (Bondarko & Semenov, 2005; Norgett & Siderov, 2014) producing similar crowding function shapes. Our conclusion that flankers should be placed closer to the target than they are in currently available charts, would still apply. The results of the present study, during which many hours of data collection were needed and not possible in children, may be applicable to children, although it would now be valuable to test some select conditions on children.

5. Conclusion

In summary, the results indicate that (1) the placement of surrounding features reveal more consistent crowding effects if they are specified in stroke- and not optotype-widths, (2) crowding features should be placed closer than they are on currently available commercial charts, to maximise the effects of contour interaction and crowding, (3) optimal placement of crowding features also enhances test sensitivity by increasing the psychometric function slope, which in adults is steepest at a separation of 2 stroke-widths, (4) using flankers that are similar to the target optotype produces greater crowding and increases the sensitivity of the chart. It would be valuable to further investigate the relationship between the magnitude of crowding and the slope of the psychometric function to investigate whether maximising the crowding effect, by placing crowding features at 1 stroke-width, or maximising the sensitivity of the chart, by placing the flankers at 2 stroke-widths, is more important clinically.

Disclosure

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

Acknowledgments

Sarah J. H. Lalor was funded by an Anglia Ruskin University Graduate Teaching Assistantship. This study was funded in part by a grant from the Evelyn Trust, Cambridge, U.K. Portions of this work were presented at The European Academy of Optometry and Optics annual conference in 2012.

References

Alexander, K. R., Xie, W., & Derlacki, D. J. (1997). Visual acuity and contrast sensitivity for individual sloan letters. *Vision Research, 37*, 813–819.

Anstice, N. S., & Thompson, B. (2014). The measurement of visual acuity in children: An evidence-based update. *Clinical & Experimental Optometry: Journal of the Australian Optometrical Association, 97*, 3–11.

Atkinson, J., Anker, S., Evans, C., Hall, R., & Pimm-Smith, E. (1988). Visual acuity testing of young children with the Cambridge Crowding Cards at 3 and 6 m. *Acta Ophthalmologica, 66*, 505–508.

Atkinson, J., Pimm-Smith, E., Evans, C., Harding, G., & Braddick, O. (1986). Visual crowding in young children. *Documenta Ophthalmologica Proceedings Series, 45*, 201–213.

Attebo, K., Mitchell, P., Cumming, R., Smith, W., Jolly, N., & Sparkes, R. (1998). Prevalence and causes of amblyopia in an adult population. *Ophthalmology, 105*, 154–159.

Bailey, I. L., & Lovie, J. E. (1976). New design principles for visual acuity letter charts. *American Journal of Optometry and Physiological Optics, 53*, 740–745.

Bedell, H. E., Siderov, J., Waugh, S. J., Zemanová, R., Pluháček, F., & Musilová, L. (2013). Contour interaction for foveal acuity targets at different luminances. *Vision Research, 89*, 90–95.

Beirne, R. O., McIlreavy, L., & Zlatkova, M. B. (2008). The effect of age-related lens yellowing on Farnsworth-Munsell 100 hue error score. *Ophthalmic and Physiological Optics, 28*, 448–456.

Bennett, A. G. (1965). Ophthalmic test types. A review of previous work and discussions on some controversial questions. *The British Journal of Physiological Optics, 22*, 238–271.

Bernard, J. B., & Chung, S. T. (2011). The dependence of crowding on flanker complexity and target-flanker similarity. *Journal of Vision, 11*, 1–16.

Bodack, M. I., Chung, I., & Krumholtz, I. (2010). An analysis of vision screening data from New York City public schools. *Optometry (St. Louis, Mo), 81*, 476–484.

Bondarko, V. M., & Semenov, L. A. (2005). Visual acuity and the crowding effect in 8- to 17-year-old schoolchildren. *Human Physiology*, 31, 532–538. Translated from Fiziologiya Cheloveka, Vol. 31, No. 5, 2005, pp. 44–51.

British Standards Institution. (2003). BS 4274-1:2003. Visual acuity test types – part 1: Test charts for clinical determination of distance visual acuity specification.

Candy, T. R., Mishoulam, S. R., Nosofsky, R. M., & Dobson, V. (2011). Adult discrimination performance for pediatric acuity test optotypes. *Investigative Ophthalmology & Visual Science, 52*, 4307–4313.

Cotter, S. A., Cyert, L. A., Miller, J. M., Quinn, G. E., & National Expert Panel to the National Center for Children's Vision and Eye Health (2015). Vision screening for children 36–<72 months: Recommended practices. *Optometry and Vision Science: Official Publication of the American Academy of Optometry, 92*, 6–16.

Danilova, M. V., & Bondarko, V. M. (2007). Foveal contour interactions and crowding effects at the resolution limit of the visual system. *Journal of Vision, 7*, 25.1–25.18.

Fern, K. D., & Manny, R. E. (1986). Visual acuity of the preschool child: A review. *American Journal of Optometry and Physiological Optics, 63*, 319–345.

Flom, M. C., & Neumaier, R. W. (1966). Prevalence of amblyopia. *Journal of the Optical Society of America, 81*. 329-329.

Flom, M. C., Weymouth, F. W., & Kahneman, D. (1963). Visual resolution and contour interaction. *Journal of the Optical Society of America, 53*, 1026–1032.

Flynn, J. T., Schiffman, J., Feuer, W., & Corona, A. (1998). The therapy of amblyopia: An analysis of the results of amblyopia therapy utilizing the pooled data of published studies. *Transactions of the American Ophthalmological Society, 96*, 431–450. discussion 450-3.

Flynn, J. T., Woodruff, G., Thompson, J. R., Hiscox, F., Feuer, W., Schiffman, J., ... Smith, L. K. (1999). The therapy of amblyopia: An analysis comparing the results of amblyopia therapy utilizing two pooled data sets. *Transactions of the American Ophthalmological Society, 97*, 373–390.

Formankiewicz, M. A., & Waugh, S. J. (2013). The effects of blur and eccentric viewing on adult acuity for pediatric tests: Implications for amblyopia detection. *Investigative Ophthalmology & Visual Science, 54*, 6934–6943.

Friendly, D. S. (1978). Preschool visual acuity screening tests. *Transactions of the American Ophthalmological Society, 76*, 383–480.

Herzog, M. H., Sayim, B., Chicherov, V., & Manassi, M. (2015). Crowding, grouping, and object recognition: A matter of appearance. *Journal of Vision, 15*, 1–18.

Hess, R. F., Dakin, S. C., Tewfik, M., & Brown, B. (2001). Contour interaction in amblyopia: Scale selection. *Vision Research, 41*, 2285–2296.

Holmes, J. M., Beck, R. W., Repka, M. X., et al. (2001). The amblyopia treatment study visual acuity testing protocol. *Archives of Ophthalmology, 119*, 1345–1353.

Holmes, J. M., & Clarke, M. P. (2006). Amblyopia. *Lancet, 367*, 1343–1351.

Hyvarinen, L., Nasanen, R., & Laurinen, P. (1980). New visual acuity test for pre-school children. *Acta Ophthalmologica, 58*, 507–511.

Jacobs, R. J. (1979). Visual resolution and contour interaction in the fovea and periphery. *Vision Research, 19*, 1187–1195.

Jeon, S. T., Hamid, J., Maurer, D., & Lewis, T. L. (2010). Developmental changes during childhood in single-letter acuity and its crowding by surrounding contours. *Journal of Experimental Child Psychology, 107*, 423–437.

Jones, D., Westall, C., Averbeck, K., & Abdolell, M. (2003). Visual acuity assessment: A comparison of two tests for measuring children's vision. *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists), 23*, 541–546.

Kay, H. (1983). New method of assessing visual acuity with pictures. *The British Journal of Ophthalmology, 67*, 131–133.

Kemper, A. R., Keating, L. M., Jackson, J. L., & Levin, E. M. (2005). Comparison of monocular autorefraction to comprehensive eye examinations in preschool-aged and younger children. *Archives of Pediatrics & Adolescent Medicine, 159*, 435–439.

Kooi, F. L., Toet, A., Tripathy, S. P., & Levi, D. M. (1994). The effect of similarity and duration on spatial interaction in peripheral vision. *Spatial Vision, 8*, 255–279.

Kovacs, I. (2000). Human development of perceptual organization. *Vision Research, 40*, 1301–1310.

Leat, S. J., Li, W., & Epp, K. (1999). Crowding in central and eccentric vision: The effects of contour interaction and attention. *Investigative Ophthalmology & Visual Science, 40*, 504–512.

Levi, D. M., & Carney, T. (2009). Crowding in peripheral vision: Why bigger is better. *Current Biology: CB, 19*, 1988–1993.

Levi, D. M., Hariharan, S., & Klein, S. A. (2002). Suppressive and facilitatory spatial interactions in amblyopic vision. *Vision Research, 42*, 1379–1394.

Lippmann, O. (1971). Vision screening of young children. *American Journal of Public Health, 61*. 1586-1586.

Little, J. A., Molloy, J., & Saunders, K. J. (2012). The differing impact of induced astigmatic blur on crowded and uncrowded paediatric visual acuity chart results. *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists), 32*, 492–500.

Malania, M., Herzog, M. H., & Westheimer, G. (2007). Grouping of contextual elements that affect Vernier thresholds. *Journal of Vision, 7*.

Manassi, M., Sayim, B., & Herzog, M. H. (2012). Grouping, pooling, and when bigger is better in visual crowding. *Journal of Vision, 12*(13), 1–14.

Masgoret, X., Asper, L., Alexander, J., & Suttle, C. (2011). The development of crowding and interocular interactions in a resolution acuity task. *Investigative Ophthalmology & Visual Science, 52*, 9452–9456.

Mayer, D. L., & Gross, R. D. (1990). Modified Allen pictures to assess amblyopia in young children. *Ophthalmology, 97*, 827–832.

McGraw, P. V., & Winn, B. (1993). Glasgow acuity cards: A new test for the measurement of letter acuity in children. *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists), 13*, 400–404.

McGraw, P. V., Winn, B., Gray, L. S., & Elliott, D. B. (2000). Improving the reliability of visual acuity measures in young children. *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists), 20*, 173–184.

Mercer, M. E., Drover, J. R., Penney, K. J., Courage, M. L., & Adams, R. J. (2013). Comparison of Patti Pics and Lea symbols optotypes in children and adults. *Optometry and Vision Science: Official Publication of the American Academy of Optometry, 90*, 236–241.

Morad, Y., Werker, E., & Nemet, P. (1999). Visual acuity tests using chart, line, and single optotype in healthy and amblyopic children. *Journal of AAPOS: The Official Publication of the American Association for Pediatric Ophthalmology and Strabismus/ American Association for Pediatric Ophthalmology and Strabismus, 3*, 94–97.

Norgett, Y., & Siderov, J. (2014). Foveal crowding differs in children and adults. *Journal of Vision, 14*(23), 1–10.

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision, 4*, 1136–1169.

Pelli, D. G., Robson, J. G., & Wilkins, A. J. (1988). The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Sciences, 2*, 187–199.

Salt, A. T., Wade, A. M., Proffitt, R., Heavens, S., & Sonksen, P. M. (2007). The Sonksen logMAR test of visual acuity: I. Testability and reliability. *Journal of AAPOS: The Official Publication of the American Association for Pediatric Ophthalmology and Strabismus/American Association for Pediatric Ophthalmology and Strabismus, 11*, 589–596.

Scherf, K. S., Behrmann, M., Kimchi, R., & Luna, B. (2009). Emergence of global shape processing continues through adolescence. *Child Development, 80*, 162–177.

Schlenker, M. B. B., Christakis, T. J. J., & Braga-Mele, R. M. M. (2010). Comparing a traditional single optotype visual acuity test with a computer-based visual acuity test for childhood amblyopia vision screening: A pilot study1. *Canadian Journal of Ophthalmology/Journal Canadien d'Ophtalmologie, 45*, 368–374.

Schmucker, C., Grosselfinger, R., Riemsma, R., Antes, G., Lange, S., Lagrèze, W., et al. (2009). Effectiveness of screening preschool children for amblyopia: A systematic review. *BMC Ophthalmology, 9*, 1–12.

Shah, N., Laidlaw, D. A., Rashid, S., & Hysi, P. (2012). Validation of printed and computerised crowded kay picture logMAR tests against gold standard ETDRS acuity test chart measurements in adult and amblyopic paediatric subjects. *Eye (London, England), 26*, 593–600.

Sheridan, M. D., & Gardiner, P. A. (1970). Sheridan-Gardiner test for visual acuity. *British Medical Journal, 2*, 108–109.

Siderov, J., Waugh, S. J., & Bedell, H. E. (2013). Foveal contour interaction for low contrast acuity targets. *Vision Research, 77*, 10–13.

Simmers, A. J., Gray, L. S., & Spowart, K. (1997). Screening for amblyopia: A comparison of paediatric letter tests. *The British Journal of Ophthalmology, 81*, 465–469.

Simons, K. A. (2005). Amblyopia characterization, treatment, and prophylaxis. *Survey of Ophthalmology, 50*, 123–166.

Solebo, A. L., & Rahi, J. S. (2013). Vision screening in children aged 4–5 years. External review against programme appraisal criteria for the UK National Screening Committee (UK NSC). Available at <http://legacy.screening.nhs.uk/vision-child>.

Song, S., Levi, D., & Pelli, D. (2014). A double dissociation of the acuity and crowding limits to letter identification, and the promise of improved visual screening. *Journal of Vision, 14*, 1–37.

Stuart, J. A., & Burian, H. M. (1962). A study of separation difficulty. Its relationship to visual acuity in normal and amblyopic eyes. *American Journal of Ophthalmology, 53*, 471–477.

U.S. Preventive Services Task Force (2004). Screening for visual impairment in children younger than age 5 years: Recommendation statement. *Annals of Family Medicine, 2*, 263–266.

Vision in Preschoolers Study Group (2005). Preschool vision screening tests administered by nurse screeners compared with lay screeners in the vision in preschoolers study. *Investigative Ophthalmology & Visual Science, 46*, 2639–2648.

Weibull, W. (1951). A statistical distribution function of wide applicability. *Journal of Applied Mechanics, 18*, 293–297.

Williams, C., Gilchrist, I. D., Fraser, S., McCarthy, H. M., Parker, J., Warnes, P., ... Hyvarinen, L. (2015). Normative data for three tests of visuocognitive function in primary school children: Cross-sectional study. *The British Journal of Ophthalmology, 99*, 752–756.