Visual acuity in children: the development of crowded and single letter acuities

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Abstract

Previous research has explored the development of visual acuity in babies and children, and it has been established that the measured visual acuity is dependent on the method used. In the present study developmental trends in crowded versus single letter visual acuities were explored. 343 children, 5 to 11 years of age, were tested using Glasgow Acuity Cards (GAC), and a significant correlation between binocular visual acuity and age was found using simple regression analysis ($y = 0.023x + 0.81$, $r2 = 0.32$). Mean values of crowded visual acuity varied between 0.95 ± 0.06 logMAR in 5-year-olds to 1.08 ± 0.09 logMAR in 11-year-olds. One way ANOVA confirmed the developmental trend [$F(1, 341) = 160.45$, $p < 0.0001$]. In a second study, these results were replicated in a smaller group of fully corrected children (regression analysis showed significant development with age, $y = 0.025x + 0.86$, $r2 = 0.429$, one way ANOVA: [$F(1, 72) = 54.11$, $p < 0.0001$]. The repeatability of the GAC was tested using a test-retest strategy, 6 months apart. A significant improvement of monocular visual acuities at the retest may be explained, at least in part, by the expected development of visual acuity during this period. A single letter acuity test was constructed by matching GAC optotypes. Fifty two emmetropic children (mean age 8.21 ± 1.76 years) were tested on both tests. Developmental trends were then compared for single and crowded acuities. Linear regressions were $F(1, 50) = 23.87$, $p = 0.0001$, $y = 0.019x + 0.915$, $r2 = 0.31$ for crowded letters and $F(1, 50) = 5.81$, $p < 0.05$, $y = 0.009x + 1.07$, $r2 = 0.104$ for single letters. Repeated measures ANOVA (test * age) showed reliable differences for both main effects. Single letter acuity was found to display a very slight developmental trend, and was better than crowded acuity. When deciding normal values and cut-off limits, one must take into consideration which test is being used, as normative data will not directly translate from one test to another.

Introduction

The vision of a newborn baby may be compared to viewing a scene through a mist—the outline of shapes is indistinct, brightness sensitivity is reduced and colours appear unsaturated (McCulloch, 1998). Visual acuity develops rapidly during the first six months of life. In normal development, the rate of visual improvement slows down after the first six months and gradually approaches adult levels (e.g. Atkinson, 1984). The age at which visual acuity reaches adult levels depends on the test employed: One of the main differences between the reported levels of visual acuity is whether the acuity is assessed using single optotypes (symbols) or a line of symbols, which includes contour interaction and/ or crowding.

A number of studies have explored the development of visual acuity in children. For charts which use single letters, an acuity level of 6/4.5 has been suggested as a normal monocular value for five to seven year old children (Sheridan, 1974) and five to six year old children (Atkinson, Pimm-Smith, Evans, Harding, & Braddick, 1986). Some investigators have suggested that a single letter acuity of 6/9 should be regarded as subnormal monocular acuity for this age group (e.g. Sheridan, 1974; Jayatunga, Sonksen, Bhide, & Wade, 1995) whereas others have recommended the cut-off at 6/12 (e.g. Hall, 1989) - giving an extremely good

specificity at the cost of a very low sensitivity (Jayatunga et al. 1995). When deciding normal values and cut-off limits, one must take into consideration which test is being used, as normative data will not directly translate from one test to another (Fern & Manny, 1986, Norgett & Siderov, 2011). Visual acuity assessed with a line of symbols has been found to give a lower measure of acuity in children than single letters (Sheridan, 1974; Fern & Manny, 1986). Normal values have been suggested as 6/6 for linear charts and 6/7.5 on a multiple optotype array for five to seven year olds (Atkinson et al. 1986), although a progressive improvement over the primary school ages has been observed (Kothe & Regan, 1990; Salt, Sonksen, Wade, & Jayatunga, 1995). See Table 1 for conversion between Snellen and logMAR scores for visual acuity.

The reduction of visual acuity with multiple optotypes is referred to as "visual crowding", "lateral masking" or "contour interaction". The terms are often used interchangeably, but may be distinguished. The crowding effect may be estimated by comparing single letter acuity and acuity with multiple arrays, giving a so-called "crowding ratio" with a ratio greater than 1.0 indicating visual crowding (Flom, Heath, & Takahashi, 1963; Flom, Weymouth, & Kahneman, 1963).

It seems that line acuity matures more slowly, and maturation is suggested to occur at around 10 years of age (Hohmann & Haase, 1982). A recent study of the effect of different crowded test designs as opposed to single optotype tests, concluded that line acuity was still maturing between 4 to 9 years (Norgett & Siderov, 2011). Visual acuity as assessed by isolated, single optotypes appears to approach adult levels at a young age. Several investigators (e.g. Atkinson et al. 1986; Fern, Manny, Davis, & Gibson, 1986) have suggested that the decreased level of line acuity cannot be caused by immature resolution but is rather a result of lateral interactions. These conclusions have been challenged by Kothe and Regan (1990) who compared Snellen line acuity and "repeat-letter flash cards". The repeat-letter flash cards maintained a constant relationship between letter size and spacing (i.e. the crowding was constant) regardless of visual acuity level. Kothe and Regan found that the crowding effect was not different for the oldest and youngest age groups: i.e., both single letter and crowded letter acuity showed similar improvements in the age range tested (4 to 11 years). On the basis of these results, Kothe and Regan suggested that a delayed development of the ability to select and/or direct gaze was a principal explanation for the high crowding effect on the line chart. The suggestion that the more prominent crowding effect observed in younger children may be due to either immature oculomotor control or attentional or cognitive factors is supported by Norgett and Siderov (2011).

Part I. Visual screening and developmental trend of crowded visual acuity

The main aim of the present study was to investigate the developmental trend of crowded visual acuity in school age children. A benefit of the visual screening that was carried out was the recruitment of participants for further studies, which included investigations into various aspects of visual function. The

study presented in the present paper was the first part of a larger study, which included investigations into various aspects of visual function.

Part II. Crowded and single letter visual acuity in emmetropic children

A second study was undertaken to: (i) explore the test-retest reliability of the Glasgow Acuity Cards; (ii) discover whether the change in visual acuity with age presented in Part I was due to uncorrected refractive error (i.e. in Part II the participating children were refracted and only those with emmetropia were included within the visual acuity study); (iii) investigate visual crowding by comparing line and single optotype acuity.

Methods
Part I

A relatively large school in the north of Scotland with a wide social-cultural catchment area was contacted to gain access to carry out this project. The protocol presented to the school included a visual screening of all children, resulting in a report and referral in cases of previously undetected visual problems (see below). Ethical permission from the local educational authorities was sought and gained before the commencement of the study. The study (Part I and II) followed the tenets of the Declaration of Helsinki. Prior to the vision screening a letter describing the project was sent to all parents/guardians. A positive response was required if the child was not to participate in the project. Of the 433 letters sent out, 11 (2.5%) letters were returned, requesting exclusion from the study. Another eight children (1.8%) were not screened due to absence from school.

A total of 414 children were run through the screening procedure. Children with high refractive errors, strabismus, amblyopia and obvious oculomotor problems were identified and a report was sent to the school and to parents/guardians if the observed visual problems were previously undiagnosed, in order to allow appropriate intervention to take place. Children who passed the criteria listed below were included in an evaluation of the developmental trend of crowded visual acuity.

All children underwent a testing procedure consisting of:

1. Distance visual acuity using the Glasgow Acuity Cards (GAC). If the child wore glasses for distance vision on a regular basis, corrected visual acuity was recorded
2. Cover test at near and distance
3. The Lang stereoacuity test
4. Assessment of motility and pupil reflexes
5. Near point of convergence (NPC)
6. A positive lens test, consisting of a pair of +2.00D child-size spectacles. As well as a subjective response of blur, visual acuity on GAC was noted
7. Objective refraction by retinoscopy was carried out for the youngest children (4 to 5 years of age)

Visual Acuity Recording

Binocular and monocular corrected or uncorrected visual acuities were recorded using the Glasgow Acuity Cards (GAC), also known as the logMAR Crowded test. This test is designed for accurate measurement of "crowded" visual acuity in children (McGraw & Winn, 1993) and incorporates several features to ease visual acuity testing in young children. The testing distance of

3 m allows better communication and easier testing of children and has no adverse effect on the acuity compared to acuity testing at the standard 6 m distance (Atkinson, Anker, Evans, Hall, & Pimm-Smith, 1988). The GAC incorporate a linear progression of letter size (log scale), with 0.1 log unit between each line. This regular geometric progression allows parametric statistical analysis of results. Each line has an equal number of letters (four) allowing crowding to be constant across the acuity levels and only a limited selection of letters of approximately equal legibility is used. All letters are symmetrical about the vertical axis to avoid confusion in young children (it has been shown that children develop horizontal- before vertical laterality, e.g. Graham, Berman, & Ernhart, 1960). The test is based on line acuity with surrounding contours to make it sensitive to amblyopia. Crowding is standardised at each acuity level by using appropriate spacing between each letter and a size controlled crowding bar surrounding the four letter array. Simmers, Gray and Spowart (1997) have reported that the Glasgow Acuity Cards provide greater sensitivity for assessing interocular differences than the traditional single optotype format. (GAC and Sheridan-Gardiner test detected 100% and 55% of unilateral amblyopia respectively). The scoring system of the GAC is based on the log of the minimum angle of resolution (MAR). Unlike other logMAR scale tests (such as the Bailey-Lovie chart, Bailey & Lovie, 1976), the original GAC designated Snellen acuity 6/6 (decimal VA 1.0) a score of one (1.0) and Snellen acuity 6/60 (decimal visual acuity 0.1) a score of zero (0.0), with negative values for acuities less than 6/60 (e.g. an improvement in visual acuity gives a higher acuity score). "Snellen acuity" is defined by a fraction where the numerator denotes the testing distance (usually 6 m) and the denominator denotes the letter size (the size where the letter stroke subtends 1 min arc at the meter distance given). The relationship between the original GAC and the traditional logMAR score is: GAC score = 1 - logMAR. The original designation for GAC is used throughout this paper. The GAC score is similar to the decimal visual acuity which is the most used designation in clinical practices in the Scandinavian countries: the better the visual acuity, the higher the score. See Table 1 for a reference to traditional logMAR. The later version of the test, the logMAR Crowded test, uses traditional logMAR.

Table 1: Visual acuity scores showing Snellen fraction, decimal acuity, logMAR and Glasgow Acuity Card (GAC) scores

Snellen fraction	Decimal acuity	logMAR	GAC
6/3	2.0	-0.3	**1.3**
6/3.75	1.6	-0.2	**1.2**
6/4.75	1.25	-0.1	**1.1**
6/6	1.0	0.0	**1.0**
6/7.5	0.8	0.1	**0.9**
6/9.5	0.6	0.2	**0.8**
6/12	0.5	0.3	**0.7**
6/15	0.4	0.4	**0.6**
6/19	0.3	0.5	**0.5**
6/24	0.25	0.6	**0.4**
6/30	0.2	0.7	**0.3**
6/38	0.15	0.8	**0.2**
6/48	0.125	0.9	**0.1**
6/60	0.1	1.0	**0.0**

Procedure

Each child stood 3 m from the visual acuity charts, and was instructed to read out loud the letters presented. A chart comprising four letters was shown at each acuity level, starting with letters which could easily be seen. The letters were reduced in size until no optotypes could be resolved. The room was well lit by artificial light sources. Monocular visual acuity was recorded before binocular visual acuity. For recording monocular visual acuity, the child was asked to hold their cupped hand in front of one eye. The test is designed to be used with a method of forced choice: each child should be encouraged to guess at the letters in order to limit the influence of confidence and personality on the result. This procedure, however, was not strictly followed: although encouragement was given to read the letters, the children were not "forced" to guess at the next level—especially if they were slow and hesitant. This procedure would tend to result in a higher sensitivity, but a lower specificity, and for the purpose of the study it was decided that the general sensitivity of the test made this a desirable bias (i.e. the false negatives would constitute only a small number of children and it was better to be "safe than sorry").

Exclusion criteria

The criteria for failing the vision screening, resulting in exclusion from the research protocol of the two projects, were as follows:

- Visual acuity of < 0.8 on the GAC was set as the threshold for failure, which excluded those with significant uncorrected myopia and/or astigmatism. A visual acuity level of Snellen 6/9 has been suggested to be a cut-off value with high sensitivity and good specificity (Jayatunga et al. 1995), although variable criteria have been used in previous studies (Fern & Manny, 1986).
- A positive finding on the positive lens test indicating significant uncorrected hypermetropia.
- A visual acuity difference of two or more lines (equal 0.2 log units) between the two eyes, indicating amblyopia.
- Any strabismus or uncompensated heterophoria found on cover test.
- Insufficient convergence by near point of convergence > 8 cm.
- Reduced stereoacuity (negative result on Lang test, > 200").
- Any abnormal finding on motility (reduced action of one or more extra ocular muscles, any incomitancy) or pupillary reflex tests.

If a child failed any of the above criteria the guardian was notified by letter and advised to arrange for further examination by a local optometrist. If the child was already under the care of an optometrist/ophthalmologist, no further action was taken.

Part II

In the second study, a semi-random sample of 114 children from three local primary schools in Berkshire, England was recruited. Teachers were given information in advance to ensure that any child that they thought might have a previously undiscovered vision problem was included. A referral letter was sent to the parents of each child that did not pass the criteria for the vision screening, laid out above. All tests, on both visits, were carried out by the same person.

The children were run through a vision screening procedure consisting of the following:

1. Monocular and binocular visual acuity by Glasgow Acuity Cards (GAC)
2. Single letter (SL) acuity, (only those who passed the criteria for "emmetropia" listed below)
3. Cover test at near and distance
4. Near point of convergence
5. Motility
6. Pupillary reflexes
7. Retinoscopy, non-cycloplegic
8. Stereopsis (measured by Randot Stereo Test)

i) Test-retest reliability of visual acuity measured with GAC.
82 children from one school only were tested twice. Seven children were excluded due to a lack of co-operation on one of the tests or because their refractive error changed between the two sessions. Mean age at the first session was 7.75 ± 1.79 years. The second examination was carried out approximately six months later (mean age 8.28±1.81 years).

ii) Development of visual acuity over the 5 to 11 year age band.
75 children from three primary schools, mean age 8.15 ± 1.78 (range 5.33 to 11.17 years) passed the criteria for emmetropia. Simple linear regression of crowded letter visual acuity against age was carried out for monocular and binocular viewing. The same procedure for presenting letters and recording visual acuity was followed as described for Part I. In this second part, however, a strict forced choice routine was followed. Children either responded verbally or matched the letters using an appropriate key card if they were unsure about the letters.

iii) Single letter versus. Crowded letter acuity
52 children (from the same school as i)), mean age 8.21 ± 1.76 (range 5.67 to 11.17 years), who passed the criteria for emmetropia were also tested on single letters. For single letter acuity isolated letters were made up on cardboard, one letter on each plate. The same, vertically symmetrical letters were used as in the GAC and four letters were presented at each acuity level. The same logarithmic scaling system was used to allow a direct comparison with crowded acuity.

The criteria of "emmetropia" that the children had to meet to be included in the studies ii) and iii) were as follows:

- Myopia < 0.25 DS
- Hypermetropia ≤ 1.00 DS
- Astigmatism ≤ 0.50 DC
- No strabismus

Results
Part I
From the 414 children that were screened, 50 (12.1%) were referred for a further eye examination with a local optometrist. The various reasons for referrals are summarised in Table 2. An additional 19 (4.6%) children who were already under ophthalmic care were excluded from further study because their visual acuities were not within the normal range.

Simple regression analysis was performed on the data for the remaining 345 children and the correlation between age and vi-

Table 2: 50 children were referred for further eye examination for the reasons listed

Principal reason for referral	Number of referrals
Decreased visual acuity	21
Un-/Undercorrected hypermetropia	22
Convergence insufficiency	4
Unrecognised strabismus	1
Other	2

sual acuity was investigated to reveal any developmental pattern within the age group 5 to 11 years. One way ANOVA revealed that the effect of age was reliable [$F(1, 341) = 160.45$, $p < 0.0001$] and a significant correlation was found between binocular visual acuity and age ($y = 0.023x + 0.81$, $r2 = 0.32$), (see Figure 1). Similar results were obtained for monocular acuities (OD: $y = 0.024x + 0.76$, $r2 = 0.31$ $p < 0.0001$; OS: $y = 0.024x + 0.77$, $r2 = 0.33$, $p < 0.0001$), but no reliable differences were found between the acuity levels recorded for the right and left eyes (mean levels were 0.974 ± 0.083 and 0.977 ± 0.081 for right and left eyes respectively). The mean and standard deviations of binocular visual acuities are listed for each age group and for boys and girls separately in Table 3.

The group included in Part I of the study comprised 183 females and 162 males (52.7% and 47.3% respectively). A two-way ANOVA was performed to investigate any difference in visual acuity by gender and showed reliable main effects (age and gender). The interaction, however, was not significant. Boys had better visual acuity than girls by a mean difference of 0.035 logMAR; $F(1, 329) = 14.707$, $p < 0.0001$. The significant correlation with age shown by simple regression above was confirmed by ANOVA; $F(6, 329) = 30.44$, $p < 0.0001$. Tukey-HSD post-hoc comparison showed that all of the oldest age groups (≥ 8 years) had significantly higher visual acuity than all the younger children (≤ 7 years).

Figure 1. Binocular visual acuity (GAC score) plotted for the 343 of the 345 children who passed the screening. A significant correlation was found between age and binocular visual acuity ($y = 0.023x + 0.81$, $r2 = 0.32$).

Part II

i) Test-retest Reliability

The results from the test and retest were compared using two-tailed t-test for paired observations. The means and standard deviations of crowded letter acuity for both test and retest are listed in Table 4. Monocular acuities for both right and left eye were found to be significantly different on the two occasions; $t(74) = -2.474$, $p < 0.05$ and $t(74) = -2.945$, $p < 0.005$, for right and left eye respectively. Binocular visual acuity, however, was not found to be reliably different on the two occasions; $t(46) = -1.141$, $p < 0.05$.

A repeated measure ANOVA (test-retest age) was performed to evaluate whether repeatability was affected by age group. A test-retest effect was significant for monocular but not for binocular visual acuity. A main age effect was reliable (see ii). An interaction was significant only for left eye monocular visual

Table 3: Mean values for binocular visual acuity (GAC score) for the different age groups

Group	5 years	6 years	7 years	8 years	9 years	10 years	11 years	All ages
All	0.952 ± 0.063	0.949 ± 0.053	0.992 ± 0.068	0.995 ± 0.048	1.038 ± 0.057	1.065 ± 0.067	1.080±0.091	1.014±0.079
Boys (B)	0.983 ± 0.041	0.958 ± 0.058	1.003 ± 0.064	0.997 ± 0.045	1.043 ± 0.051	1.078 ± 0.068	1.117±0.096	1.033±0.079
Girls (G)	0.935 ± 0.068	0.943 ± 0.050	0.983 ± 0.071	0.994 ± 0.051	1.032 ± 0.064	1.050 ± 0.064	1.045±0.071	0.998±0.076
n (B/G)	42 (15/27)	37 (15/22)	54 (22/30)	52 (22/30)	60 (33/27)	57 (30/27)	43 (21/22)	343 (160/183)

Note. Two results are missing as monocular acuities only were recorded in two children

Table 4: Mean and standard deviation of crowded letter acuity (GAC score)

	VA, 1st test (test)	VA, 2nd test (retest)	Signed difference (test/retest)	Unsigned difference (test/retest)
RE	0.990 ± 0.076	1.01 ± 0.077	0.018 ± 0.061	0.048 ± 0.041
LE	0.981 ± 0.077	1.01 ± 0.077	0.024 ± 0.068	0.053 ± 0.048
Binoc.	1.026 ± 0.077	1.046 ± 0.074	0.011 ± 0.061	0.047 ± 0.040

Note. The signed difference denotes a positive value for an improvement at the second test, whereas a decline in visual acuity would be a negative value. The unsigned difference between test and retest uses absolute values, so that a decrease in visual acuity in one child does not null out an increase of visual acuity in another child.
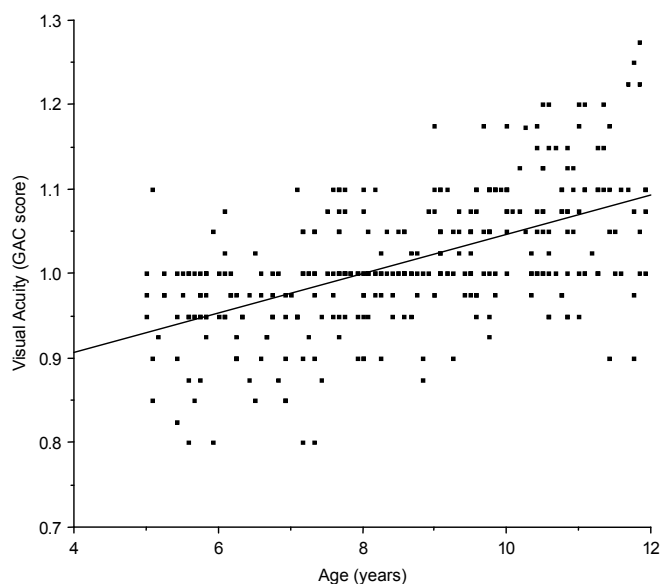
acuity; F(5, 66) = 2.76, p < 0.05. Measures from right eye and binocular acuity tended to be less variable (less improvement in acuity from test to retest) with age. Consistent with the significant differences found between test and retest, Pearson two-tailed correlations between the two recordings were strong at 0.688, 0.614 and 0.685 for right eye, left eye and binocular visual acuity respectively.

ii) Development of visual acuity over the 5 to 11 year age band.
Simple regression analysis of visual acuity records obtained from 75 children (of which two obtained monocular visual acuity only) showed that in emmetropic eyes, crowded visual acuity was significantly correlated with age. For binocular visual acuity: F(1, 72) = 54.11, p < 0.0001, y = 0.025x + 0.86, r2 = 0.429. Monocular analysis was similar. Two-tailed unpaired t-test and two-way ANOVA were used to investigate the effect of gender on visual acuity (measures were obtained from both crowded and single letter cards). Mean binocular crowded acuity was 1.07 ± 0.07 and 1.05 ± 0.06 for boys and girls respectively (monocular acuities: OD: 1.03 ± 0.07 and 1.02 ± 0.07, OS: 1.03 ± 0.06 and 1.01 ± 0.07). No reliable differences between genders were found. Records from 52 children's single letter acuity showed different developmental trends than that of the crowded letter acuities. Single letter acuity matures at a lower age than crowded letter acuity, and simple regression analysis only just reached significance for binocular visual acuity (F(1, 50) = 5.81, p < 0.05, y = 0.009x + 1.07, r2 = 0.104).

iii) Single letter versus crowded letter acuity.
In the previous section (ii) regression analysis was outlined to illustrate the developmental trend. For direct comparison between the two tests, simple regression for crowded acuity was also calculated on the children (n = 52) who were tested on single optotypes. One child was defined as an outlier (below 2 SD of the mean) for crowded visual acuity and excluded from statistical analysis. The linear regression for binocular acuity was; F(1, 49) = 23.87, p < 0.0001, y = 0.019x + 0.915, r2 = 0.31, and for single letters was; F(1, 50) = 5.81, p < 0.05, y = 0.009x + 1.07, r2 = 0.104 (see Figure 2). Monocular acuity data were similar. Polynomial or logarithmic regression did not give an improved fit of the data.

A repeated measures ANOVA (test * age) was used to investigate main effects of the different tests and ages. Both main effects showed reliable differences between the age levels. Results are given for binocular visual acuity only, monocular results were similar. Main effect of different tests showed that there was a reliable difference in the visual acuity measured with GAC crowded letters and single letters; F(1, 44) = 123.96, p < 0.0001. From Table 5 it can be seen that single letter visual acuity is generally better than that obtained using crowded letters. Main effect of

age groups (results from both crowded and single letter acuities are joint) were also significant; F(1 ,44) = 4.19, p < 0.005, but the interaction was not reliable; F(6, 44) = 1.64, p > 0.05. Paired t-tests confirmed the difference in visual acuity obtained on the two tests; t(50) = -10.64, p < 0.0001.
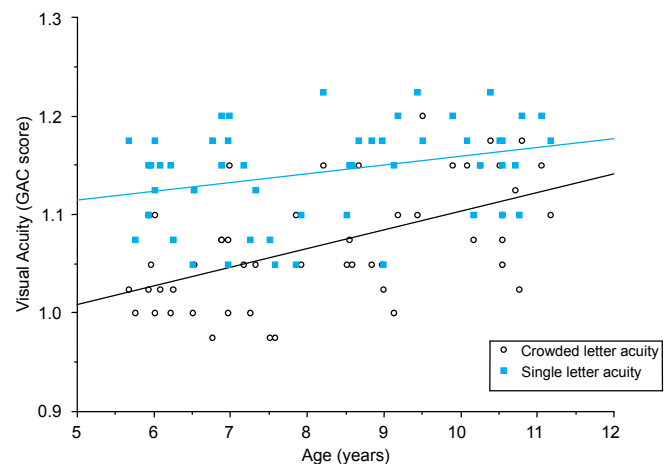

Figure 2. The binocular visual acuities (GAC scores) for the 52 children tested on both crowded and single letter charts are plotted together. A significant correlation with age was present for crowded letters (y = 0.019x + 0.915, r2 = 0.31). Regression analysis for single letter acuity was less reliable (y = 0.009x + 1.07, r2 = 0.104).

Discussion
Part I
It was previously assumed that young children reach adult levels of visual acuity by the age of 4 to 5 years (e.g. Fern & Manny, 1986). Such assumptions were based on studies which used single letter charts. More recent studies have found that visual acuity measured with optotypes that incorporate contours and crowding is reduced (e.g. Morad, Werker, & Nehmet, 1999; Levi & Carney, 2009; Norgett & Siderov, 2011) and has a different developmental trend (Drover et al., 2008; Sonksen, Wade, Proffitt, Heavens, & Salt, 2008; Norgett & Siderov, 2011) in comparison to acuity achieved by single letter optotypes. In the present study, single letters and the crowded Glasgow Acuity Cards were used. The results in this study are consistent with previous studies where visual acuity tested with single optotypes has been found to be better than that measured with crowded acuity charts.

A reliable correlation was found between age and visual acuity with the acuity increasing with age by the rate of 0.023 logMAR per year in the age group 5 to 11 years. It should be noted that no check was made to ensure that the participants were fully corrected for refractive error. It is possible that some of the children may have had uncorrected myopia or astigmatism, which would have decreased uncorrected visual acuity by a few lines

Table 5: Binocular visual acuities (GAC scores) for crowded and single letters for each age group separately

Test	5 Yrs	6 Yrs	7 Yrs	8 Yrs	9 Yrs	10 Yrs	11 Yrs
GAC	1.04 ± 0.04	1.03 ± 0.06	1.03 ± 0.05	1.08 ± 0.05	1.11 ± 0.07	1.11 ± 0.05	1.13 ± 0.04
Single Letters	1.13 ± 0.04	1.14 ± 0.05	1.09 ± 0.04	1.15 ± 0.05	1.19 ± 0.03	1.15 ± 0.04	1.19 ± 0.02
n	5	14	7	8	5	11	2

Note. The same 52 children are included for each test.

although still being within the criterion limit. In particular astigmatism could have been significant without visual acuity being affected to an extent that it would meet the exclusion criteria. Astigmatism affects visual acuity less than the same amount of spherical ametropia and visual acuity is normally a poor identifier of uncorrected astigmatism.

The results showed that boys had slightly better visual acuity than girls. These results are in agreement with previous studies by Burg (1966) and by Brown and Yap (1995). Using Bailey-Lovie type charts, they found that males had significantly better acuity than females by 0.03 logMAR. The finding is difficult to explain, and no physical and/or physiological explanation is presently available. The behavioural aspects of such a difference by gender, however, cannot be ruled out. It is possible that boys in general are more confident and more likely to make a guess at letters around threshold. In the results from Part II where a strict forced choice regime was followed – when each child was forced to make a choice around threshold, the difference in achieved visual acuity between the two genders disappeared. This result reinforces the need to use a force choice strategy when testing young children. It should be noted that although the difference in visual acuity between boys and girls found in this first study was statistically reliable it has no clinical significance. In contrast, the differences in visual acuity between the youngest and the oldest children have clinical significance.

Part II

The differences in mean visual acuity between test and retest (0.02 and 0.03 for right and left eyes respectively) reached statistical significance in monocular measurements which was due in part to the very low variance. It is worth noting, however, that there was a general trend for the visual acuity to improve at the second recording. In light of the strong age effect found this might be due to an actual improvement in visual acuity over the six month period rather than reflecting a weakness in the vision screening method used. It was found that crowded acuity increased by 0.025 logMAR per year, which explains half of the difference over the six month interval. Considering the results in a clinical rather than statistical context, the repeatability was quite good. An unexplained difference of 0.025 logMAR equals only one letter within the test. A correlation of about 0.66 also indicates a robust test, although, as usual when testing children, some variability is difficult to avoid. The conclusion of a robust test is in line with a previous reliability study performed by the developer of the Glasgow Acuity Cards (McGraw, Winn, Gray, & Elliott, 2000). Similar reliable measures of linear visual acuity was found using the Sonksen logMAR test (Salt, Wade, Proffitt, Heavens, & Sonksen, 2007) which uses a separation of 1.0 letter-width as opposed to the smaller 0.5 letter-width of the GAC. Using the Lea Symbols Chart which utilizes a line-by-line testing regime and constant crowding, the test-retest reliability (within the same test session) was found to be good in amblyopic children (Chen, Chandna, Norcia, Pettet, & Stone, 2006).

The developmental trend found in the first study (Part I) was replicated in the second study where all the children were emmetropic. Although the mean improvement in visual acuity (0.025 logMAR) per year was very slight, it is evident that crowded acuity does not seem to have reached a fully developed level in the youngest children. Single letter acuity was found to display a very slight developmental trend over the age span tested.

This agrees with previous studies which have reported that single letter acuity is well developed by primary school age (Fern & Manny, 1986). These findings again stress the need to utilise a forced choice method if accurate and objective measurements of visual acuity are to be made.

Single letter visual acuity was better than crowded visual acuity in children aged 5 to 11 years. It is well established that single letters are not sensitive to amblyopia when measuring visual acuity in young children (nonetheless, single letters are often used). In a study by Morad and colleagues (1999) the difference between logMAR visual acuity for full chart, single line and single optotypes were compared for healthy and for amblyopic eyes. The improvement of logMAR visual acuity for single letters as compared to a single line was confirmed in this study, but they also found a similar further decrement in visual acuity when testing with a full chart in comparison to single lines. This effect was found in both amblyopic and in control eyes, but the effect was stronger for the amblyopic eyes. The crowding effect of a single line was found to be half the effect of a full chart, and illustrates how the crowding effect seems to be a continuum rather than an all-or-nothing phenomenon. This result stresses the need to monitor the test mode throughout the examination, during any treatment and for follow up.

Norgett and Siderov (2011) compared different test designs; charts with different amount of contour interaction as well as crowded versus single letter charts. The logMAR Crowded test has an inter-optotype spacing of 0.5 letter-width, whereas the Sonksen logMAR test has less contour interaction with an inter-optotype spacing of 1.0 letter-width. These were compared to a crowded symbol test, the Crowded Kay Picture test, as well as two single optotype tests: the Single Kay test (symbols) and the Sheridan Gardiner test, which uses single letters. It was shown that the test with more contour interaction, namely the logMAR Crowded test was more difficult to perform for both the young (4-6 years) and older (7-9 years) test groups. Visual acuity depended on the type of optotypes used and symbols gave better acuity than letters. It was also found that crowding effect was more prominent in the youngest age group, in line with the significant age effect found in the present study.

Although the developmental trend in crowded acuity was stronger than the trend found for single letter acuity, the interaction between the two tests was not statistically reliable. This indicates that the developmental rates of the two visual abilities tested were not statistically different and that single letter acuity was not fully matured in the youngest children tested in this study.

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