AOSIS

Test–retest reliability of contrast visual acuities in a clinical population

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Background: Previously, contrast visual acuities (VA) have been evaluated as a potential screening, diagnostic and predictive tool in cases where standard visual acuity remains intact. Issues around contrast acuity sometimes make it difficult for clinicians to make appropriate clinical decisions and thus such tests have to be standardised and reliable.

Aim: To investigate test–retest reliability of contrast VA in healthy adults in a clinical setting.

Methods: Best compensated contrast VA at 100%, 10%, 5% and 2.5% of 155 patients (mean age 39.7 ± 12.2 years) were measured using the computerised Thomson Test Chart 2000 Expert. For all participants and at each contrast level, two measurements per right eye were determined. Test–retest reliability for the four contrast levels were assessed using reliability coefficients and Bland–Altman plots. Participants were also divided into three age groups of young (18–39 years, $n = 72$), middle-age (40–49 years, $n = 45$) and elderly (50–67 years, $n = 38$) and reliability was assessed within and between age and gender groups.

Results: For the whole-sample test and retest, measurements within each contrast level were not statistically different ($p \geq 0.05$). Thus, test and retest measurements per participant were averaged and whole-sample mean-contrast VA and standard deviations for 100%, 10%, 5% and 2.5% were -0.146 ± 0.060, 0.050 ± 0.071, 0.135 ± 0.079 and 0.405 ± 0.115 logMAR, respectively. Significant differences were found between all pairs of contrast levels compared ($p \leq 0.0125$). Mean-contrast VA within each age group were also significantly different across all contrast levels ($p < 0.0001$). Mean-contrast VA at each contrast level between the age groups indicated that mean-contrast VA were not significantly different between the young and middle-age groups ($p > 0.05$) but were statistically different between the young and elderly groups ($p < 0.01$). Only mean-contrast VA 10% was significantly different between the middle-age and elderly groups ($p < 0.001$). Also, mean-contrast VA for the four contrast levels within gender were significantly different ($p \leq 0.05$) but not between genders ($p \geq 0.05$).

Conclusion: This study found good reliability of test and retest measurements of contrast VA in an adult clinical population.

Introduction

Contrast visual acuities (VA) are an important psychophysical measure of visual or functional dysfunction, and contrast VA are also useful in monitoring the effects of disease-modifying therapies.[1,2,3,4,5,6,7,8,9] Clinical contrast VA tests, readily available in both printed and computerised charts, are easy to use and generally reliable.[9,10,11,12,13,14,15] Contrast VA measurements at different contrast levels form isolated points on an individual's contrast sensitivity curve, and shifts in these curves become diagnostically important in detecting subtle changes of the visual system, especially in certain pathological conditions where patient's present with 6/6 visual acuity.[2,6,9,10] Contrast sensitivity testing has been used with ocular diseases (particularly cataract, glaucoma, diabetes mellitus and age-related macular degeneration) and in predicting mobility and functional vision.[6,16,17,18,19,20] Predominantly, high (100%) and medium (10%) contrast levels have been assessed in studies evaluating refractive surgery outcomes,[21,22] performances of contact lenses[4,5,23] and activities of daily living.[6,17,24] For example, Bailey et al.[22] used 100% contrast levels and 18% contrast levels (which they defined as low contrast although 18% would generally be considered a medium-contrast level) to evaluate the effects of LASIK pre-operatively and 3 and 6 months post-operatively. Low-contrast levels have been evaluated in studies for diagnosing ocular diseases and in monitoring therapeutic interventions.[25] Recently, with highly active therapy regimes (such as nutritional supplementation, pharmacologic treatments, gene therapy, macular translocation surgery, retinal prosthetic implants, photodynamic therapy or foetal cell transplantation), early detection of ocular complications has become even more critical, as some of the disease complications can be halted or even reversed with these treatments. There are several reports

showing evidence that during asymptomatic stages of retinal diseases such as diabetic retinopathy or glaucoma (where visual acuity remains good or fairly good), alterations occur in the retinal ganglion cells and in the inner retinal neurons.[18,19,25,26,27]

Contrast sensitivity testing as a potentially valuable clinical measurement has not attained wide acceptance as an additional routine visual screening or examination procedure among optometrists and ophthalmologists, despite the above evidence. A possible reason may be inconsistent results obtained from various studies. For example, studies suggest that contrast sensitivity is affected by many ophthalmic diseases, but not all affected patients show similar changes in contrast sensitivity.[18,19,25,27] Secondly, patients with different ophthalmic diseases may show apparently similar changes in contrast sensitivity.[28,29,30] However, these discrepancies may also be due to possible limitations or differences in the study methodology (e.g. the use of monocular data in some studies but binocular data in others) and the nature of the contrast sensitivity test itself (charts with different targets or test distances or luminance). Thirdly, the number of spatial frequencies or contrast levels evaluated in studies are not consistent as some authors evaluated only two (mostly high and low) levels,[1,24,26,31,32,33,34] some three[6,35] and some four or more.[1,15,33,36] Other authors have suggested that in most clinical or perhaps even research situations, only one or perhaps two levels of contrast actually need to be measured and methods such as factor analysis have been used to provide support for this assertion.[24,26,29,33,34]

All types of contrast sensitivity letter charts have some advantages for clinicians and patients; they are relatively inexpensive, easy and quick to administer and are generally considered diagnostically sensitive despite some of the limitations already mentioned.[1,37,38] Not unexpectedly, patients without ocular disease do show some variability in threshold testing but patients with disease may exhibit even greater variability.[6,16] To aid in efficient clinical management, criteria must be established for objective assessment and comparison of results. Therefore, this study firstly and primarily investigates *test–retest* reliability of contrast VA measurements (at 100%, 10%, 5% and 2.5% contrast levels) both *within* and *between* contrast levels, and secondly, investigates whether contrast VA measurements, as obtained with a commercially available computer-based test, are perhaps influenced by age or gender.[39]

Methods
Study population and setting

One hundred and fifty five (N = 155) participants were recruited from a private optometry practice located in Johannesburg, South Africa. Only participants over the age of 18 years were included in the study. Participation was voluntary, and informed and signed consents were obtained. Ethical clearance for the study was obtained (AEC45/01-2011) from the Ethics Committee of the Faculty of Health Sciences

of the University of Johannesburg. Only participants without systemic or ocular diseases and without medications, or of ocular surgery or significant vision loss were included. Measurements of all parameters occurred in one clinical environment with the same ambient (mesopic) lighting conditions. Tests were performed in a specific diagnostic sequence and all participants had distance VA of 6/6 or better in each eye with their best compensated subjective refractions.

Procedures

A basic biographical, general health and ocular history questionnaire was first administered to all participants. The questionnaire concerned demographical aspects (date of birth, age, race and gender), general health and basic systemic conditions (hypertension, respiratory problems, renal conditions, central nervous system conditions or other diseases) and vision-related questions (e.g. if they had any history of ocular surgery and/or diseases, use of medication and headaches). These questions were included to eliminate possible factors that could cause changes in vision involving the eye and retina.

Subjective clinical refractions were performed on all participants to determine best compensated VA for distance (6 m). Stereo-acuity, cover test and Ishihara colour vision tests were administered as additional diagnostic tests to determine if any binocular or colour anomalies were present. Direct ophthalmoscopy and biomicroscopy were used to detect any abnormalities of the ocular media and/or fundi.[40]

Contrast visual acuity assessment

Contrast VA with their subjective refractions (best compensated VA) were measured with the Thomson Test Chart 2000 Expert software.[39] This software can generate a wide range of test charts and stimuli, but for this study Bailey-Lovie logMAR charts with 4 × 5 British Sloan letters consisting of, Z, V, P, H, E, F, R, D, U and N were used. Each chart consisted of five of the above letters and a uniform logarithmic progression in size of letters on each line with randomisation of letters as displayed. The contrast of these letters was then reduced from 100% to 10%, 5% and 2.5% and measurements were taken accordingly. For statistical analysis, responses were recorded using the 'letter score' method[40,41] and then converted[41] to logMAR scores. The test charts were automatically displayed on a Samsung SyncMaster Series 5, 24 inch widescreen LED monitor, as per the recommendations of the test manufacturer (Thomson), which complies with the European and British standards for adequate display of test charts.[39]

In order to minimise variation of measurements created by the test itself, both the letter size and monitor luminance of the charts were calibrated as follows: (1) To ensure that the letters subtended the correct angle at the eye, we manually confirmed the automatic computerised calibration by calculating and measuring the letter height subtending an angle of 5 min arc at a viewing distance of 4.12 m.[40] The height of this letter, an

'E' in the 6/6 line, was approximately 6 mm as measured with a millimetre rule. (2) Luminance of the screen target (letter) and background at each of the four different contrast levels were measured using a photospectrometer (the Photo Spectrascan) and averages of three measurements per level were applied to the Weber formula.[42] For example, at 100% contrast maximum luminance, Lmax (white ground luminance) = 246.3 cdm^{-2}, whereas the minimum luminance, Lmin (black target/stimulus luminance) = 0.8419 cdm^{-2}. These measurements with the Weber formula indicated that the contrast was 99.66% for the 100% contrast levels, and at 2.5% the contrast equated to 2.395%.

Two measurements (test and retest) per chart (100%, 10%, 5% and 2.5%) for the compensated right eyes of each of the 155 participants were obtained. Before analysis, all data were carefully examined for possible errors, for example, by checking each of the variables for measurements that were out of the expected ranges, and where necessary corrections were made.

Statistical analysis

The Statistical Consulting Department of the University of Johannesburg assisted with planning and advice regarding data analyses of contrast VA using the Statistical Package for Social Sciences (SPSS, version 21). In some instances, the researchers also used Statistica- or Matlab-based software, for example, for Bland–Altman plots and their analysis. Preliminary analyses were then performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity.[43,44] Test and retest reliabilities at the various contrast levels were assessed using correlation coefficients, intra-class correlation coefficients (ICCs), coefficients of repeatability (CRs) and limits of agreement (LoA). Bland–Altman plots and LoA[45] (mean difference ± 1.96 standard deviation [s.d.]) are commonly used in various optometry and ophthalmology studies to assess agreement – see the dashed lines in Figure 1 for an example of such LoA. Importantly, McAlinden et al.[46] suggested that confidence intervals (CIs) on such LoA should also be calculated and reported. Thus, here, LoA and their CIs (grey filled intervals surrounding dashed lines in Figure 1 for the upper and lower LoA) were included, together with the respective mean difference or bias (solid black lines in, for example, Figure 1), respectively, in tables and also on the Bland–Altman plots concerned.

Thereafter, the appropriate statistical tests (non-parametric tests, analysis of variance and *post hoc* tests) were employed to explore the relationships among variables (e.g. differences between test and retest data for the whole sample or for sub-groups according to gender and age).

Results

This clinical sample of 155 participants had a mean age and s.d. of 39.7 ± 12.2 years; 80 (51.6%) were male and 75 (48.4%) were female, and 73 (47.1%) were of Indian descent.
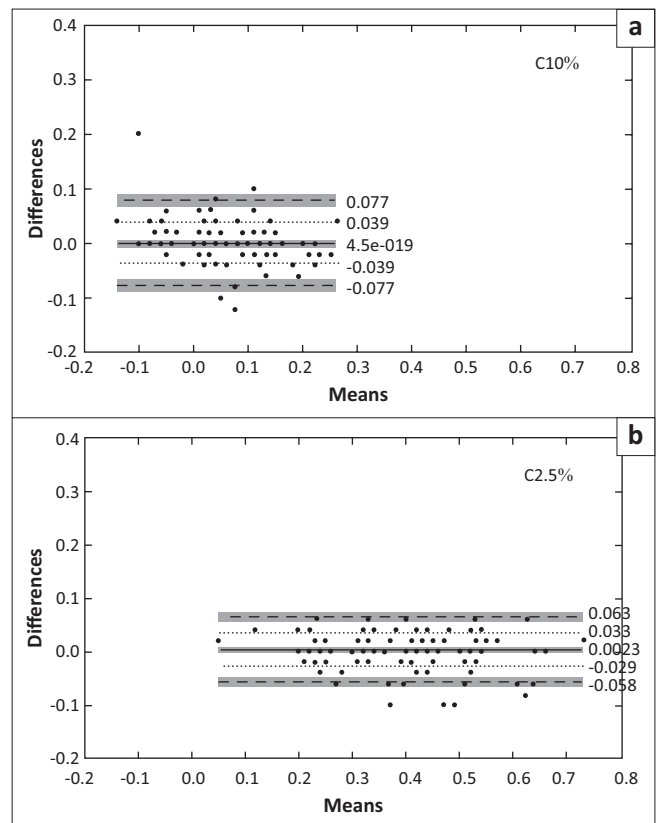
Both Bland–Altman plots have the same scales for easier comparisons. The horizontal solid black lines represent the mean differences and for both contrast levels the mean differences are small and close to zero. The black dotted lines above and below the solid lines on each graph represent the mean difference ± 1 standard deviation. Two black dashed lines above and below the solid black line on each graph represent the mean difference ± 1.96 standard deviations, respectively, and represent the upper and lower limits of agreement (LoA). Shaded grey regions indicate 95% confidence intervals about the mean differences and also the LoA. Irrespective of contrast level, the majority of the points fall within their 95% LoA. Possible outliers are seen outside the 95% LoA or sometimes towards the lower or upper limits of the *x*-axis for the means of test and retest data.

FIGURE 1: Bland–Altman plots for the differences (in logMAR) of test and retest measurements against their means (logMAR) for (a) 10% and (b) 2.5% contrast levels for the sample of 155 right eyes.

The remaining participants were mostly Caucasian or African. Mean intraocular pressure (and s.d.) were 13 mmHg ± 3 mmHg for the right eyes only, and mean clinical refractive status for all (155) right eyes was -0.70 – 0.14 × 7.

Comparison between test and retest contrast visual acuity measurements

Table 1 includes descriptive and correlation statistics for the test and retest measurements at the four different contrast levels (100%, 10%, 5% and 2.5%) for all participants in this study. Hereafter, the samples for a specific contrast level were indicated with the letter C in front of the contrast percentage; thus for 100% contrast the sample is C100. With Kolmogorov-Smirnov tests, the C100 test and retest samples, the C10 test and retest samples, the C5 test and retest samples and also the C2.5 retest samples all had probability values of $p < 0.0001$, suggesting departure from data normality ($p < 0.05$). The C2.5 test was the only data displaying normality ($p = 0.20$). As seven of the eight samples here were not normally distributed, mainly non-parametric analyses were employed for further analysis. The mean-contrast VA decreased as contrast levels decreased (from 100% to 2.5%), indicating that participants found it more difficult to correctly

identify letters at the lower contrast levels (Table 1). Test and retest means for participants varied minimally: by 0.001 logMAR for contrast 100% (C100), zero logMAR or 0.08 letters for contrast 10% (C10), 0.005 logMAR for contrast 5% (C5) and 0.003 logMAR for contrast 2.5% (C2.5). The s.d. of the means also increased slightly as contrast decreased; however, contrast VA (and their s.d.) seemed to be fairly consistent when comparing test and retest measurements. The test and retest medians were also very consistent (contrast level 5% varies by 0.02 logMAR or only one letter). Significant and strong, positive correlations between test and retest measurements for all contrast levels were observed in this study. The correlations for the 2.5% test and retest measurements were higher when compared with the 100% level and these results probably may be attributed to participants who generally tended to concentrate more when viewing the more difficult lower contrast letters as compared with the 100% level which was much easier to read. Another reason may be attributed to truncation of the letter chart where -0.20 logMAR was the smallest line to be read, thus resulting in a ceiling effect in some eyes where perhaps smaller letters (on the high-contrast chart mainly) might otherwise have been resolved.

Correlation coefficients only measure the strength of a relation between two variables and not the agreement between them. According to Bland and Altman[44] and McAlinden et al.,[46] repeatability of measurements is effectively assessed using the LoA technique and therefore important statistics for the LoA between test and retest measurements for the 155 right eyes and also some measures of repeatability for the four contrast levels are included in Table 2.

The mean-contrast VA (in Table 2) for the whole sample is defined as the overall average of the test and retest measurements, which were themselves averaged across the 155 eyes. Differences were determined by subtracting the test score of each eye from its retest score. In Table 2, the mean-contrast VA and s.d. for contrast level C100 is -0.147 ± 0.060; therefore -0.147 − 0.060 = -0.207 or 6/3.7 and -0.147 + 0.060 = -0.087 logMAR or $\approx 6/4.8^{-0.5}$. This indicates the mean-contrast VA (-0.147) was approximately $6/3.8^{-2.5}$ and about 68% of the measurements were between $6/3.8^{-2.5}$ and $6/4.8^{-0.5}$, and 95% would be between the mean ± 1.96 s.d. Using letter count, the s.d. approximates to about three letters for C100, about 3.5 letters for C10, about four letters for C5 and about five letters for C2.5, indicating that variation in contrast VA measurements increases slightly as contrast levels decrease. The mean differences between 155 test and retest measurements were small and almost zero, irrespective of contrast level. The s.d. of the mean differences in letters ranged from 1.5 to 2 letters or 0.03–0.04 logMAR, indicating minimal variation between the test and retest measurements. Individual right eyes might, however, have shown larger differences between test and retest measurements.

With all contrast levels, the standard errors (see Table 2) for the *respective* mean differences are small. Generally, LoA are also small and the 95% CIs for the mean differences and for the upper and lower LoA are relatively narrow, indicating that the mean differences and the interval estimates are very precise.
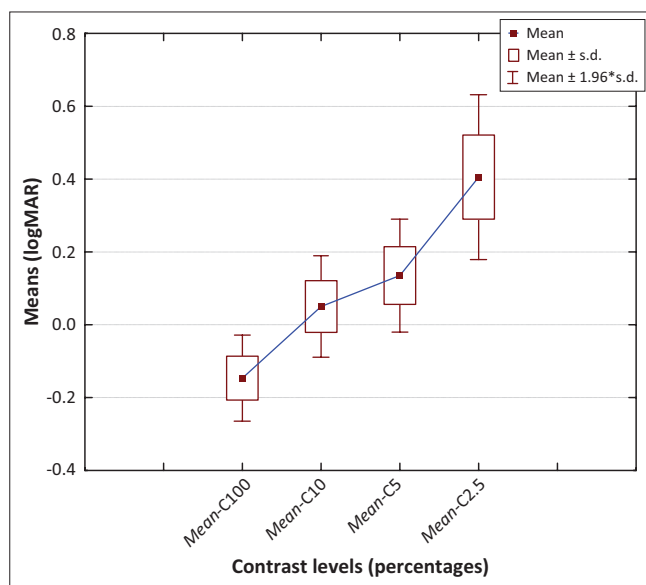
The four CRs are almost zero, and the ICCs in Table 2 for all contrast levels are approximately 1, indicating high levels of consistency or reliability between test and retest measurements for each of the four contrast levels. These results suggest little in the way of learning or fatigue effects with these participants. Of these, C10 had the highest CR value of ≈ 0.08, indicating that test and retest measurements

TABLE 1: Means, standard deviations, medians and interquartile ranges for test and retest measurements for contrast visual acuities of the right eyes of 155 participants at contrast levels 100% (C100), 10% (C10), 5% (C5) and 2.5% (C2.5).

Contrast Level	Mean	s.d.	Median	IQR
C100 Test	-0.146	0.062	-0.180	0.10
Retest	-0.147	0.061	-0.180	0.06
C10 Test	0.050	0.077	0.040	0.10
Retest	0.050	0.069	0.040	0.10
C5 Test	0.138	0.082	0.140	0.08
Retest	0.133	0.079	0.120	0.06
C2.5 Test	0.404	0.117	0.420	0.18
Retest	0.407	0.116	0.420	0.14

Results indicate consistent test and retest measurements and significant positive linear correlations (for Pearson's $p < 0.01$ and Spearman's rank-order correlations, $p < 0.0005$). For C100, test and retest samples were strongly correlated ($r = 0.90$, $p = 0.72$), and similarly for C10 ($r = 0.86$, $p = 0.81$), C5 ($r = 0.94$, $p = 0.87$) and C2.5 ($r = 0.97$, $p = 0.96$). Units are logMAR throughout the table.

TABLE 2: Descriptive statistics and limits of agreement between the test and retest measurements for 155 right eyes for four contrast levels, namely 100%, 10%, 5% and 2.5%. Standard errors and confidence intervals for mean differences ($\overline{\chi}_d$) and LoA are also included. Measures of repeatability such as coefficients of repeatability and intra-class correlation coefficients are also provided.

N = 155	100%	10%	5%	2.5%
Mean-contrast VA (s.d.)	-0.147 (0.060)	0.050 (0.071)	0.135 (0.079)	0.405 (0.116)
Mean differences ($\overline{\chi}_d$) (s.d.)	-0.000 (0.027)	0.000 (0.040)	-0.005 (0.0286)	0.002 (0.031)
Standard error for $\overline{\chi}_d$	0.002	0.003	0.002	0.003
95% CI for $\overline{\chi}_d$	-0.005; 0.004	-0.006; 0.006	-0.009; -0.000	-0.003; 0.007
LoA: $\overline{\chi}_d \pm 1sd$	-0.027; 0.027	-0.039; 0.039	-0.033; 0.024	-0.029; 0.033
$\overline{\chi}_d \pm 1.96sd$	-0.055; 0.053	-0.077; 0.077	-0.062; 0.052	-0.058; 0.063
Standard error of LoA	0.004	0.006	0.004	0.004
CI of upper LoA	0.045; 0.060	0.067; 0.088	0.043; 0.059	0.054; 0.071
CI of lower LoA	-0.062; -0.047	-0.088; -0.067	-0.069; -0.053	-0.067; -0.050
CR	0.053	0.077	0.057	0.061
ICC	0.904	0.857	0.935	0.965

were slightly less similar, but the presence of outliers were important in this sample and may have influenced the result (see Figure 1a where four measurements were outside the 95% LoA).

For simplicity, Figure 1 includes only two (10% and 2.5%) of the four contrast levels, but all Bland–Altman plots revealed that the majority of the points were located relatively near to the solid black line representing the applicable mean difference for the contrast level concerned. Most points for each contrast level were located within their 95% LoA, and so largely irrespective of contrast level the variability of the differences in test and retest measurements was small: about 1.5 letters (approximately 0.03 logMAR) for C100, C5 and C2.5; and two letters (or 0.04 logMAR) for C10%; thus, only two plots are provided here (see Figure 1). The Bland–Altman plots indicated that the distributions of the differences between the test and retest contrast VA scores for all four contrast levels reflected minimal variability and therefore generally the test and retest scores can be considered to be in good agreement.

Wilcoxon signed-rank tests for the four paired comparisons (i.e. between test and retest measurements for C100, C10, C5 and C2.5) revealed that for all contrast levels, test and retest contrast VA were not statistically different ($p \geq 0.05$), suggesting that there were minimal learning and fatigue effects (or that these two effects cancelled each other out). Consequently, for each eye and for all four contrast levels, corresponding test and retest contrast VA measurements were averaged resulting in one sample of *Mean*-contrast VA per contrast level. These four new samples of *Mean*-C100, *Mean*-C10, *Mean*-C5 and *Mean*-C2.5 ($N = 155$ for each sample) were used for further analysis instead of

the eight test and retest samples and this simplifies such an analysis.

Using the Friedman's chi-squared test, a statistically significant difference in *Mean*-contrast VA for 100%, 10%, 5% and 2.5% contrast levels was found ($\chi^2_{3,155} = 460.98$, $p < 0.0001$, *Mean*-C100 -0.147 ± 0.060 logMAR; *Mean*-C10 0.050 ± 0.071 logMAR; *Mean*-C5 0.135 ± 0.079 logMAR and *Mean*-C2.5 0.405 ± 0.116 logMAR). Thereafter, *post hoc* comparisons were conducted to determine which *Mean*-contrast VA pairs were significantly different from one other based on the mean ranked differences of each. The Wilcoxon signed-rank test was performed and a Bonferroni correction was applied (the alpha level, usually 0.05, was divided by the number of variables [four here because of the four different contrast levels]). Thus, $p = 0.05/4 = 0.0125$ and all pairs of samples of *Mean*-contrast VA compared (Figure 2) were statistically different ($p < 0.0125$).

Comparison of contrast visual acuities means within and between genders

The study sample consisted of 80 males (mean age and s.d. of 39.67 ± 12.48 years) and 75 females (mean age and s.d. of 39.73 ± 12 years). *Within* gender, Friedman tests indicated that mean-contrast levels within the males and also within the females were significantly different across the four contrast levels: for males, $\chi^2_{3,80} = 237.13$, $p < 0.0001$; and for females, $\chi^2_{3,75} = 223.86$, $p < 0.0001$. With *post hoc* tests and the Wilcoxon signed-rank test with a Bonferroni correction of $p = 0.013$, it was found for both the males and females that *within* each gender, there were statistically significant differences between the various contrast levels.

Mann-Whitney U tests revealed that *means* for the averaged test and retest contrast measurements for all levels were not significantly different (i.e. $p > 0.05$) between males and females (*Mean*-C100 $z = -1.416$, $p = 0.16$; *Mean*-C10 $z = -0.505$, $p = 0.61$; *Mean*-C5 $z = -0.506$, $p = 0.61$; and *Mean*-C2.5 $z = -0.973$, $p = 0.33$).

Comparison of contrast visual acuities means between different age groups

The 155 participants were divided into three age groups consisting of young pre-presbyopic adults ($n = 72$) of age 18–39 years, middle-age adults ($n = 45$) of age 40–49 years and elderly ($n = 38$) of age 50–67 years. The Friedman test found significant differences ($p < 0.05$) for *mean*-contrast VA level within each age group: in the young age group $\chi^2_{3,72} = 214.535$, $p < 0.0001$; in the middle-age group $\chi^2_{3,45} = 133.897$, $p < 0.0001$; and in the elderly group $\chi^2_{3,38} = 112.567$, $p < 0.0001$. These analyses indicated that within each age group, contrast VA at the four contrast levels 100%, 10%, 5% and 2.5% were significantly different from each other.

Box and whisker plots in Figure 3 are used to graphically compare *Mean*-contrast VA of the three age groups at the four contrast levels as investigated. The Kruskal–Wallis analysis of variance revealed that *Mean*-contrast VA varied significantly

The sample means are -0.147 logMAR (for *Mean*-C100 or 100% contrast) and 0.050 logMAR (for *Mean*-C10) and 0.135 logMAR (for *Mean*-C5) and 0.405 logMAR (for *Mean*-C2.5). A statistically significant difference in the means (small squares in the figure) for *Mean*-contrast VA for the four contrast levels was found after a Bonferroni correction (to $p < 0.0125$) was applied. The whiskers represent the mean ± 1.96 s.d. for specific samples.

FIGURE 2: Box and whisker plots are used to compare samples of *mean*-contrast VA (solid small squares) at four different contrast levels (100%, 10%, 5% and 2.5%) for 155 right eyes.

($p < 0.05$) across all age groups for all contrast levels: *Mean*-C100 $\chi^2_{2,155} = 10.390$, $p = 0.01$; *Mean*-C10 $\chi^2_{2,155} = 15.535$, $p < 0.0001$; *Mean*-C5 $\chi^2_{2,155} = 11.998$, $p < 0.01$ and *Mean*-C2.5 $\chi^2_{2,155} = 11.161$, $p < 0.01$.

Post hoc tests were conducted to determine for which age groups the mean (contrast VA) differences were present. The Mann-Whitney U test was used to test for these differences and Bonferroni adjustments (to set more stringent alpha values because of the number of tests and samples) were made.[47]

The Mann-Whitney U analyses tested the following three pairs:

- Pair 1: *Mean*-C100, C10, C5 and C2.5 in the young *versus* the middle-age group.
  Results indicated that *Mean*-C100 ($z = -2.01$, $p = 0.04$), *Mean*-C10 ($z = -1.37$, $p = 0.17$), *Mean*-C5 ($z = -1.82$, $p = 0.07$) and *Mean*-C2.5 ($z = -2.08$, $p = 0.04$) were not significant between the young and middle-age groups ($p > 0.03$, 0.05, 0.03 and 0.02, respectively).

- Pair 2: *Mean*-C100, C10, C5 and C2.5 in the young *versus* the elderly group.
  Results indicated that *Mean*-C100 ($z = -3.00$, $p < 0.01$), *Mean*-C10 ($z = -3.90$, $p < 0.0001$), *Mean*-C5 ($z = -3.38$, $p < 0.01$) and *Mean*-C2.5 ($z = -3.28$, $p < 0.01$) were significantly different between the young and elderly groups ($p < 0.05$, 0.002, 0.03 and 0.01, respectively).

- Pair 3: *Mean*-C100, C10, C5 and C2.5 in the middle-age *versus* the elderly group.
  Results indicated *Mean*-C100 ($z = -1.48$, $p = 0.14$), *Mean*-C5 ($z = -1.58$, $p = 0.11$) and *Mean*-C2.5 ($z = -1.15$, $p = 0.25$) were not significantly different between the middle-age and elderly groups ($p > 0.03$, 0.03 and 0.05, respectively).
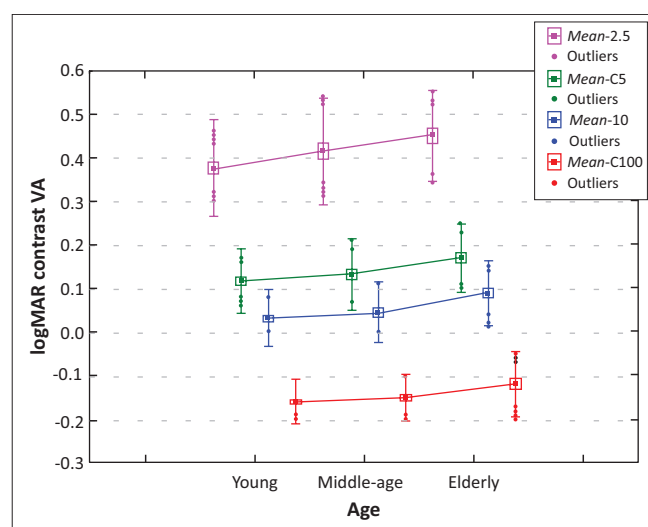
The *y*-axis is contrast VA in logMAR. Statistically significant differences for all levels of contrast VA were found between the young age and elderly groups (for all contrast levels the blue line is below the green line) and for *Mean*-C10 contrast VA between the middle-age and elderly groups but not for *Mean*-C100, *Mean*-C5 or *Mean*-C2.5. The small solid squares represent the means, surrounding boxes represent the mean ± 1 standard error and the whiskers represent the mean ± 1 standard deviation.

FIGURE 3: Box and whisker plots are used for comparison of the *Mean*-contrast visual acuities between young (18–39 years, *n* = 72), middle-age (40–49 years, *n* = 45) and elderly (50–67 years, *n* = 38) age groups.

Mean-C10 contrast VA in the middle-age group was significantly different ($p < 0.02$) to the elderly group ($z = -2.49$, $p = 0.01$).

In conclusion, the results indicated that means (of test and retest) contrast VA at each of the four levels were significantly different between the young and elderly eyes, but not between the young and middle-age eyes. For the middle-age and elderly eyes, only *Mean*-contrast VA at the 10% level was different at a 95% level of confidence.[47]

Discussion

The results of this study for the whole sample (155 right eyes), firstly, suggest that contrast VA at each of the levels of 100%, 10%, 5% and 2.5% demonstrated no significant statistical differences between test and retest measurements. Thus, such measurements with the computerised method were consistent and repeatable. Secondly, once test and retest contrast VA for each contrast level for each participant were averaged, statistically significant differences for the whole sample across the four contrast levels were found. That is, as contrast level reduces from 100% to 2.5%, mean-contrast VA for the group decreases. Thirdly, there were no real differences found between the two genders for either contrast VA means or their variations, and thus, test and retest measurements were consistent both within and across gender. Analyses of mean-contrast VA between age groups indicated that variability in responses was consistent at all four contrast levels. Means were also consistent between the younger and middle-age groups, and between the elderly and middle-age groups. However, in high-, medium- and low-contrast VA, means were found to be statistically different between the young (18–39 years) and elderly (50–67 years) age groups, despite the differences in sample sizes (72 vs. 38).

Direct comparisons of our results to other publications are difficult to make because of the different clinical and statistical methodologies and analyses used between studies. However, Ehrmann et al.[12] also found test and retest measurements for the Thomson Test Chart 2000 PRO (an earlier software version to the one that we used) to be very repeatable in terms of 100% and 10% contrast VA. The Thomson Test Chart was used to cross-validate 100% and 10% contrast VA data using traditional Bailey-Lovie paper charts and the Thomson Test Chart 2000 PRO. In their study, habitual contrast VA was measured both monocularly and binocularly at 6 m in 40 healthy adult subjects (mean age of 36 years compared with 155 subjects with a mean age of 39.7 years in this study). Using the VA group data for the computerised measurements for right eyes only (*monocular*) from their study, the means and s.d. for 100% and 10% contrast VA were -0.02 ± 0.10 logMAR and 0.22 ± 0.13 logMAR, respectively. In our study, contrast VA for both these contrast levels were found to be better and the means and s.d. for 100% and 10% contrast VA were -0.147 ± 0.06 logMAR and 0.050 ± 0.07 logMAR, respectively. Thus, the difference of means (between the two studies) for 100% and 10% equates to 0.123 and 0.17 logMAR, respectively, corresponding to a six letter difference for 100%

and an eight and half letter difference for 10% contrast VA. The difference in s.d. for both contrast levels is only about two letters (0.04 logMAR). Thus, the *monocular* results from Ehrmann et al.[12] for the means are somewhat different to results obtained from our study. The better contrast VA obtained from this study is probably attributed to measuring contrast VA with optimal refractive compensation (and VA better than 0 logMAR) when compared with Ehrmann et al.[12] where contrast VA was obtained with habitual vision (a minimum VA 6/12 for 100% contrast and 6/19 for 10% contrast). When comparing the *binocular* computerised VA group data from Ehrmann et al.[12] with means for contrast VA results from our study, similar or more consistent results were found (the *binocular* mean and s.d. for 100% and 10% contrast VA were -0.08 ± 0.08 logMAR and 0.09 ± 0.09 logMAR, respectively). Here the difference in means equates to 0.06 logMAR (or three letters) and 0.04 logMAR (or two letters) for 100 and 10%, respectively. The differences in s.d. for each contrast level were only one letter (0.02 logMAR). A maximum of a three and a half letter difference for means and a one letter difference for s.d. may be considered small; thus, in this comparison results are found to be consistent. Therefore, the Bland–Altman plot for the binocular 100% contrast VA for the monitor chart included by Ehrmann et al.[12] can be compared with the 95% LoA results for the 100% contrast level from our study. For their sample, the mean difference was almost zero (0.0004 logMAR) and the LoA were 0.073 and -0.065 logMAR. These results are similar to those in our study (a mean difference of -0.0003 logMAR and for the 95% LoA upper and lower limits of 0.053 and -0.055 logMAR). The slightly smaller or narrower (and thus more reliable) LoA found in our study may also be attributed to the reasons previously mentioned; that is, in our study a larger sample size was used and contrast VA were obtained with best compensated refractions rather than subjects using their habitual compensations or none at all.[12] In conclusion, results obtained from our study are found to be fairly consistent with the binocular results from Ehrmann et al.[12] in terms of contrast VA means and s.d. for the 100% and 10% contrast levels and in terms of repeatability for the 100% contrast level.

Further comparisons of 100% and 2.5% contrast VA from a cross-sectional observational study by Pineles et al.[20] with disease-free controls (*n* = 324) can be made to our study. Their 100% mean-contrast VA (measured with the ETDRS chart at 3.2 m) compares our results with only a two letter difference. Their 2.5% mean-contrast VA (measured with a Sloan chart at 2 m) compares with a three letter difference in our study. In their study, the mean age was 40 ± 11 years, whereas in ours, the mean age was 39.7 ± 12.2 years; in our study, all levels of contrast VA were tested using the Bailey-Lovie Sloan chart at 6 m. So, different test distances and charts are possible factors that may have led to the slight differences in contrast VA of the two studies concerned.

Results from our study are consistent with studies which reported no association of gender with contrast VA.[15,48]

The Smith-Kettlewell Eye Research Institute also evaluated gender differences with regard to night driving self-restrictions and vision function in an elderly population of 376 males and females. The vision tests evaluated subjects' binocular habitual corrections with the Bailey-Lovie high (90%) and medium or low (18%) contrast VA charts, the Pelli-Robson contrast sensitivity chart, the low-contrast, low-luminance acuity SKILL cards, the Frisby stereo test and the Berkeley glare test.[33] For the contrast sensitivity and high- and low-contrast VA tests, small but statistically significant differences (gender in ANOVA) were found between men and women drivers on low- (or medium-) contrast VA (18%) and contrast sensitivity only with women having slightly better vision than men. Possible explanations for the differences found in contrast VA for low contrast between genders and between the studies are unclear but perhaps the use of different contrast charts or other physical (e.g. foveal density) or psychological factors of the individuals concerned may be possible factors that contribute to this disparity.

The distribution of mean 100% contrast VA within a large, clinically healthy population[49] generally correlates with our results. Comparisons of 100% contrast VA could be made with results of Elliot et al.[49] in 223 subjects. Their mean-contrast VA compared well with our mean 100% contrast VA in the respective age groups. The comparisons demonstrated that in their young group (18–39 years) mean VA of -0.145 (*n* = 77) was similar to our -0.159 logMAR (*n* = 72), essentially only a single (1) letter mean difference. In their middle-age group (40–49 years), they found mean VA of -0.125 (*n* = 40) compared with our -0.149 logMAR (*n* = 45), also signifying only a single letter difference on average between the two studies. However, in their elderly group (50–67 years), they found mean VA of -0.08 (*n* = 63) compared with our -0.1187 logMAR (*n* = 38) or a two letter (mean) difference.

The means and s.d. of the younger group from our study for 100% (-0.16 ± 0.05 logMAR) and 10% (0.03 ± 0.06 logMAR) contrast VA can also be compared with results from Hazel and Elliott[50] (mean age of 28 years, with VA > 6/6). Test and retest habitual high-contrast VA were evaluated[50] monocularly (using letter-by-letter scoring) using four charts, namely the Bailey-Lovie, ETDRS, Regan and Waterloo, and low-contrast VA Bailey-Lovie 10% and Regan 11% contrast charts in 40 healthy subjects (mean age of 28.4 years, with VA > 6/6). As in the current study, their study also indicated that there were no significant learning effects from test to retest scores (*p* > 0.10), but a significant difference between the visual acuity scores from the four *high*-contrast logMAR charts was found. In addition, *post hoc* tests indicated better letter contrast VA from the Regan chart in comparison with the others which was attributed to the letter font type used. The repeatability of the *high*-contrast charts were similar with ICCs between test and retest data: 0.80, 0.79, 0.84 and 0.83 for high Bailey-Lovie, high EDTRS, high Regan and high Waterloo charts, respectively. For *low*-contrast charts, ICCs were 0.77 for the Bailey-Lovie 10% chart, and 0.84 for the Regan 11% chart. The ICCs for test and retest data with

the Thomson chart in our study showed slightly better repeatability for 100% and 10% contrast (ICCs of 0.90 and 0.86, respectively). These small differences in results may be attributed to chart fonts and chart designs.

Conclusion

The results from our study established good test–retest reliability of Thomson computer-based contrast VA charts and provide the statistical limits of contrast VA in a clinically healthy population, without serious visual impairment. These results also re-emphasise the need to measure VA and subsequently contrast VA, to threshold for different contrast levels and for different age groups. These can in turn be used for comparison with eyes, where a reduced level of contrast VA may have pathological or diagnostic implications. The results and methods in this study provide support for the use of a computerised and potentially useful clinical and research tool and may be used to diagnose, investigate and monitor ocular or systemic diseases with ocular manifestations, or with pre- and post-operative refractive surgery. They can also be used in other ocular investigations such as in vision therapy for amblyopia where contrast VA measurements have been found to be a more sensitive detector of visual function.

Acknowledgements

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