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How Good is Normal Visual Acuity?

A Study of Letter Acuity Thresholds as a Function of Age

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Abstract. Visual acuity levels were studied in 100 normal subjects of different ages, using a finely graduated letter chart under carefully optimized test conditions. Each line on the chart contained 10 letters of similar difficulty, arranged in random order. A statistical analysis of different response criteria showed a clear superiority of fractional criteria (e.g. 50% correct responses) over the traditional 100% correct requirement. The average difference between right and left eyes was 0.04 ± 0.15 (decimal notation). Regression analysis of the dependence of visual acuity on age showed a monotonic rise towards the age of 25 years, and a gradual decline thereafter. The most marked decline occurred after the age of 60. Age-dependent confidence intervals were tabulated. The results indicate that minor modifications of the conventional test procedure can enhance the diagnostic potential considerably.

Zusammenfassung. Visuswerte wurden an 100 normalen Versuchspersonen unterschiedlichen Alters untersucht.

Dabei wurde eine nach Experimenten und Überlegungen abgestufte Buchstabentestprobe verwendet, die unter sorgfältig optimierten Untersuchungsbedingungen dargeboten wurde. Jede Linie auf der Testprobe enthielt 10 Buchstaben von ähnlichem Schwierigkeitsgrad, angeordnet in einer zufälligen (randomisierten) Reihenfolge. Eine statistische Analyse der verschiedenen Antwort-Kriterien zeigte klar, daß fraktionierte Kriteria (z.B. 50% korrekter Antworten) überlegen sind über das traditionelle 100% richtige Ergebnis. Der durchschnittliche Unterschied zwischen dem rechten und linken Auge war $0{,}04 \pm 0{,}15$ (in dezimaler Aufzeichnung).

Die Untersuchung der Abhängigkeit der Sehschärfe vom Alter zeigte einen monotonen Anstieg bis zum Alter von 25 Jahren und einen monotonen Abstieg danach. Der deutlichste Abfall trat nach dem Alter von 60 Jahren

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auf. Altersabhängige Konfidenz-Intervalle wurden aufgelistet. Die Resultate zeigen, daß geringfügige Änderungen der üblichen Sehschärfeprüfung die diagnostische Zuverlässigkeit erheblich verbessern können.

Introduction

The assessment of visual acuity by means of letter charts has a long history. The traditions carry back to the 1860s, when Snellen [25] presented the first version of his famous chart, and Donders [8] advocated its use for simultaneous determinations of visual acuity and refractive errors. Many minor and major modifications have been proposed since that time, but even the most recently produced acuity charts deviate only marginally from the principles laid down by Snellen [23]. Nearly all contemporary charts are constructed on the basis of Snellen's 'norm value' for normal visual acutiy, i.e. 20/20 or its equivalent in other notation. Many charts do not contain letters corresponding to higher acuity levels. However, both Snellen [25] and Donders [8] noted that acuity levels better than 20/20 were common in normal individuals, and both cautioned against a conclusion that their norm value accurately represented normal visual acuity. Unfortunately, these cautioning remarks have rarely been heeded, and detailed information on levels of letter acuity in clinically normal eyes under clinically applicable conditions is still lacking. Previous epidemiological and clinical studies [3, 6–8, 13–15, 18, 20–22, 29] have failed to answer this question for one or more of the following reasons: debatable criteria of selection of subjects and normality, debatable precision of ametropia correction, debatable test conditions, debatable definitions of response criteria, and failure to include letter lines corresponding to acuities above 20/20. The present study aimed to define normal acuity levels for an ophthalmological clientele under simple but carefully optimized conditions.

Subjects and Methods

The subjects were drawn from the consultation service of the Department of Ophthalmology at Sahlgren's University Hospital. The criteria for inclusion were unequivocally normal findings in the ophthalmological examination, ametropia of ≤ 5 D.(diopters) sphere and ≤ 2 D.cylinder and unimpaired mental functions. All patients with any disturbances whatsoever of eyelid and eye motility, pupillary function, optical media, or visual functions were excluded, as were those with known or presumed disorders of the central nervous system. The difficult task of assessing the clarity of the optical media was solved by an operational procedure: all eyes in which the fine radial striations of the papillomacular bundle of the retinal nerve fibre layer could be visualized by direct ophthalmoscopy in red-free light were held to have clear media. All examinations were made by one of the authors (L.F.).

The acuity test utilized a specially produced acuity chart. Commercial dry transfer letters (Mecanorma 'Mercator') were affixed on mat, white, acid-free cardboard. The chosen typeface was pure black *sans serif* which accurately approximated the norm for optotypes (height = 5 stroke widths). The measured average stroke width was taken as reference for the subtended visual angle: it varied $\leq 8\%$ within and between the selected letters. The height was 10% less than the norm throughout. These deviations were considered acceptable. The typeface and the letters selected are shown in Fig. 1. The selected letters are known to be of average and approximately equal difficulty for Swedish subjects (A. Hedin, personal communication). Each of the ten letters was used once on each of the nine lines of the chart, as suggested by Sloan [24]. The letters on

C D E F K M N U V X

Fig. 1. Test letters used in the present investigation

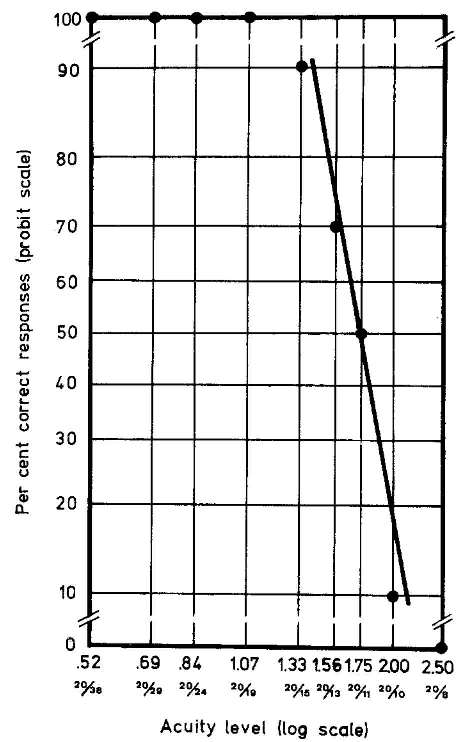

Fig. 2. Example of a test result, showing the plotting of percentage of correct responses for each test line and the fitting of a frequency-of-seeing curve

each line were arranged in random order with the restraint that only meaningless combinations were accepted. The separation between sequential letters on one and the same line equalled five strokes, according to the norm. The space in between the test lines was 40 mm.

The chart was placed 5.3 m from the subject to be tested. The acuity level corresponding to each line at this distance is given in Snellen and decimal notation in Fig. 2. The chart was illuminated by white fluorescent tubes. The luminance of the white background (L_{max}) was 400 cd/m^2 as measured with a Hagner S-2 lightmeter, while the luminance of the test letters (L_{min}) was 25 cd/m^2. The contrast, defined as $(L_{max}-L_{min})/(L_{max}+L_{min})$, equalled 0.88. Room illumination was about 300 lx. These test conditions ensured optimum results [1].

Acuity was tested monocularly, with the natural pupil [5], using the best correction found in the preceding conventional acuity test. Refractions were carried out to the nearest 0.25 D. [4]. The subject was asked to read the test lines in order from above until he came to a line where no single letter was correctly recognized. There was no time limit. The examiner noted correct responses in a special protocol. The subject was not informed about his results until testing was completed.

In subjects with bilaterally normal eyes, acuity was tested in both eyes. Some subjects with strictly unilateral abnormalities were also included: in these cases acuity was tested only in the clinically normal eye.

The test protocol immediately gave the per cent of correct responses for each line in turn. These fractions were plotted in probit units against $\log_{10}$ decimal acuity (Fig. 2). A frequency-of-seeing curve was fitted by eye to the data with the aid of a transparent ruler, giving more weight to observations near the 50% level than to other observations, to approximate a formal probit analysis [9]. The 50% and 90% thresholds were estimated graphically to the nearest 0.1 level (in decimal notation), while the 100% response criterion was taken as the finest optotype line read without any errors.

Results

This study included 100 subjects, mostly adults; 53 were females. Ametropia ranged between −5.0 D. and +3.0 D. sphere, with up to 2.0 D. cylinder. Acuity was obtained bilaterally in 70 subjects.

Visual acuity is not an all-or-none variable: no single value defines acuity exhaustively. Instead, each letter size is associated with a certain probability of correct recognition [17]. This probability may approach 100% for large letters, and diminishes gradually towards 0% for smaller letters (Fig. 2). From a statistical point of view, the 50% threshold is estimated most efficiently [9]. The 50% threshold values were quite similar in both eyes in all subjects tested bilaterally: the average difference between the right and left eyes was 0.04 ± 0.15 S.D. (decimal notation). Thus, there was no evidence of systematic differences between right and left eyes. Only one eye from each bilaterally tested subject was used in the subsequent analyses to avoid dependent observations. The right eye was selected arbitrarily. The observations from subjects with only one normal eye were added to these observations and plotted against age (Fig. 3A).

The considerable variation in visual acuity between normal individuals of the same age makes recognition of a relationship between acuity and age difficult. A polygon connecting average acuity for each age would be difficult to interpret because random sampling errors would make it jump up and down: the resulting oscillations would tend to obscure the true relationship. Another possibility of estimating the relationship is to fit a mathematical function to the data. Although this would result in a smooth curve, an erroneous assumption concerning the nature of the underlying relationship could result in misleading conclusions. Present knowledge of the shape of the relationship indicates no more than a monotonic rise in acuity from childhood to early adulthood, and a monotonic fall with advancing age [3, 6–8, 13–15, 18, 20–22, 29]. The novel tool of peak-searching regression [12], a least-squares procedure for defining single peaks or troughs among ordered observations, is appropriate in the present situation. This method gives the least-squares regression under the restriction of one local maximum or minimum, i.e. a curve rising towards a turning point, and falling thereafter (or vice versa)[1]. No information about the location of the turning point is necessary as it is obtained as a result of the analysis. The technique gives the best estimate (in a least-squares sense) of the visual acuity for each observed age. These best estimates will be the same for some adjacent ages, as can be seen in Table 1. The midpoints of these 'plateaus' have been connected by straight lines in Fig. 3a to give a smooth picture of the relationship between visual acuity and age. This approach can be viewed as a compromise between a jumping connection between raw averages, which would not utilize all the available information, and a perfectly smooth, but

1 The computer program can be obtained from the authors

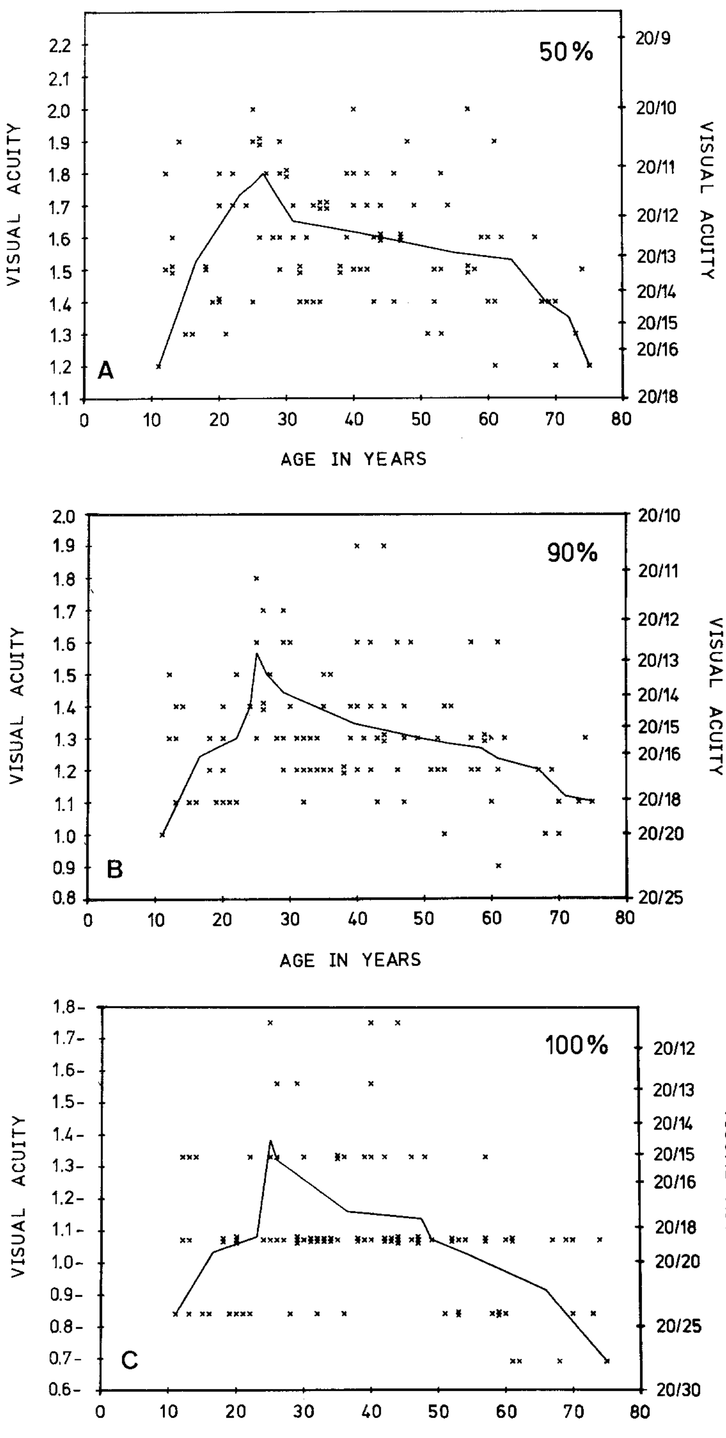

Fig. 3A–C. Letter acuity levels in 100 normal subjects plotted against age. See text for description of regression analysis. **A** 50% correct response threshold, **B** 90%, **C** 100%

Table 1. Least-squares estimate of average visual acuity in different ages

Threshold level					
50%		90%		100%	
Age	Acuity	Age	Acuity	Age	Acuity
11	1.20	11	1.00	11	0.84
12–21	1.53	12–21	1.24	12–21	1.03
22–24	1.73	22	1.30	22–24	1.08
25	1.77	24	1.40	25	1.38
26–27	1.80	25	1.57	26	1.32
28–30	1.71	26–27	1.50	27–46	1.16
31	1.65	28–30	1.44	47–48	1.13
32–49	1.61	31–48	1.34	49	1.07
51–59	1.55	49	1.30	51–57	1.03
60–67	1.53	51–57	1.28	58–74	0.91
68–69	1.40	58–59	1.27	75	0.69
70–74	1.35	60–62	1.23		
75	1.20	67	1.20		
		68–74	1.12		
		75	1.10		

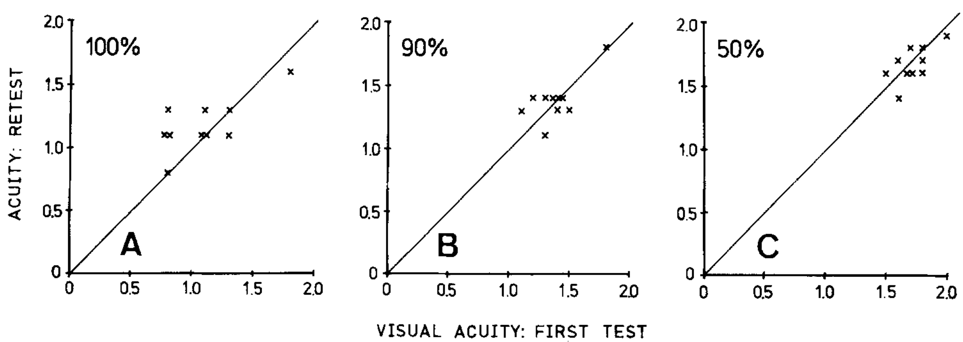

Fig. 4A–C. Within-subject variability for different response criteria. The diagonal represents perfect test-retest agreement. **A** 100% correct responses, **B** 90%, **C** 50%

possibly misleading mathematical function. Figure 3a shows that acuity rises monotonically towards a maximum at about 25 years of age, and then declines monotonically. The most marked decline occurs after the age of 60.

The 90% and 100% acuity thresholds have been plotted similarly in Figs. 3b and c. Once again, the variation between individuals is considerable, but the same trend with age occurs in all sets of observations. The results of the regression analysis are given in Table 1.

Double determinations were made on 10 individuals to separate the within-subject variability from between-subject variability. These repeat determinations were made with an interval of at least 2 months. The results are given in Fig. 4. Reproducibility appears to be fairly good for the 50% and the 90% thresholds but is much poorer for the 100% threshold. The average absolute differences were 0.11 ± 0.06 (SD), 0.10 ± 0.09, and 0.17 ± 0.17, respectively in decimal notation. This finding illuminates the large role of single errors for

Table 2. Visual acuity: averages and 95% confidence intervals for individual observations for various decades of age

Age	No.	Threshold level		
		50%	90%	100%
10–19	12	1.50; 1.13–1.87	1.23; 0.94–1.52	1.03; 0.63–1.43
20–29	20	1.69; 1.33–2.05	1.40; 1.03–1.77	1.17; 0.67–1.65
30–39	20	1.60; 1.35–1.85	1.30; 1.07–1.53	1.13; 0.88–1.38
40–49	21	1.68; 1.34–2.02	1.40; 1.00–1.80	1.23; 0.83–1.63
50–59	13	1.56; 1.19–1.93	1.28; 1.02–1.54	0.98; 0.62–1.34
60–69	9	1.50; 1.11–1.89	1.20; 0.81–1.59	0.93; 0.54–1.32
70–79	5	1.32; 1.02–1.62	1.12; 0.86–1.38	0.90; 0.46–1.34

the 100% acuity criterion. The good reproducibility observed for the two fractional criteria shows that the large span of acuity levels among normal individuals is due mainly to true between-subject variation and not to measuring errors.

The determination procedure with a fractional response criterion also easily gives a measure of its precision [9]. This can be obtained directly from the slope of the frequency-of-seeing curve. The threshold value in combination with the observed slope describes acuity completely. For the subjects tested here, the average slope (log visual acuity/probit units) equalled -17.4 ± 7.4 (SD) for the fractional criteria. A similar estimate of precision cannot be obtained for the 100% criterion.

Figure 3 indicates that age should be taken into account when evaluating a given acuity result. Average acuity levels and 95% confidence intervals for a new individual observation for each decade of age are given in Table 2. The confidence intervals are quite wide due to the large between-subject variation. Confidence intervals for averages would naturally be much narrower.

Discussion

The results described above indicate that irrespective of the actual criterion, an acuity level of only 1.0 (20/20) is quite unusual among clinically normal eyes tested under optimum conditions. Consequently, it appears fully legitimate to complain if visual acuity drops to the level of 1.0. Howe much, then, should be demanded of normal eyes? The answer obviously depends on both the criterion and the subject's age (Figs. 2 and 3). Although a 100% correct criterion is the one most commonly used, this is also the criterion that is subjected to the largest measurement variability (Fig. 4), due to the large influence of single random errors. Another disadvantage with this criterion relates to the relatively large scale factors between successive lines in presently available acuity charts. A chart having 1.0 and 1.5 as the most difficult lines does not allow precise characterization of acuity for most normal individuals (Fig. 3C). It can be calculated that a drop in acuity from 1.5 to 1.0 corresponds to a loss of 56% of the foveal cones, or their foveo-cortical neural channels [11]. A 100% correct response criterion, together with an ordinary acuity chart, would thus not allow early diagnosis of loss of foveal receptors, or disconnection of their cortical afferents.

The 90% and particularly the 50% correct criterion, have much better properties from a statistical point of view, as shown in Fig. 4. Fractional criteria have the additional advantage of being much less dependent on the scale factor between successive lines on the acuity chart. Incidentally the use of a fractional response criterion appears to offer a practical solution to the old controversy concerning the optimum lay-out of acuity charts [19, 28]. The extra work associated with the use of a fractional criterion is negligible.

The problem of early recognition of visual impairment [10] cannot be solved effectively by using single limiting acuity values, e.g. the lower bound of age-dependent confidence intervals. This requires that most individuals deteriorate severely before passing outside the limiting value. Consider for instance a 25-year-old subject with a habitual 50% acuity level of 2.1 (20/9.5): he has to deteriorate all the way down to 1.2 (20/17) before he passes outside the lower bound of his age group's 95% confidence interval (Table 2). It can be calculated that this loss of acuity is equivalent to the loss of 67% of the normal complement of foveo-cortical neural channels [11]. The problem of detecting early abnormality cannot be solved by using more refined acuity tests or refined statistical analysis, but requires additional information for its solution. Examples of additional information useful for recognizing abnormality of visual acuity when observed values fall within the normal confidence interval, include access to precise earlier measurements, and observed asymmetry between the eyes with regard to acuity, colour vision, apparent image size [11], brightness impression, and pupillary function.

While the present results indicate that normal visual acuity is considerably better than the time-honoured level of 20/20, the present data also actually underrate visual acuity somewhat because the test letters deviated up to 10% from the norm for certain details in particular letters. In most cases the deviations worked to make recognition of individual letters somewhat more difficult than expected from their stroke width.

Although a considerable body of knowledge exists concerning the physiological basis of visual acuity [10, 16, 27], very little is known about the cause(s) of its age dependence. Changes with age similar to those observed here have also been noted by other investigators. The decline with higher age may be easier to explain than the rise occurring during adolescence. The deterioration in higher age may reflect an insufficient criterion of optical clarity (Methods) [2]. Another explanation has been forwarded by Weale [26] who proposed that the change was due to an age-dependent loss of neural elements in the visual pathways.

The present results indicate that acuity charts containing 1.0 (20/20) as the most difficult test line are inappropriate for early detection of visual abnormality [10]. A useful chart should contain several lines of letters more difficult than 1.0. The scale factor between successive lines should be chosen so that frequency-of-seeing curves are defined by at least two observations. The scale factors used in the present study averaged 1.2, which appeared to be suitable. For acuities lower than 1.0, larger scale factors may be more appropriate. The optimal configuration of an acuity chart depends on several factors, particularly what use the chart is meant to fill [19]. Obviously, charts designed for evaluating needs for optical aids must be quite different from charts useful for refracting essentially normal eyes. Charts capable of detecting early disturbances of the retina and the visual pathways need several lines more difficult than the 1.0 line. The use of a fractional response criterion like the 50% threshold is indispensible in critical work.

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