Ophthalmic Epidemiology
0928-6586/98/US$ 12.00

Ophthalmic Epidemiology
– 1998, Vol. 5, No. 1,
pp. 41-53

Accepted 2 June 1997

Standardized measurement of visual acuity

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Abstract The authors reviewed the main aspects of visual acuity evaluation such as the characteristics of the test devices, the notation employed in recording the visual acuity level and the procedures for V.A. assessment, in both distance and near tests. In addition, new ten-letter charts, that tend to follow strictly the standardization guideline suggested by NAS-NRC, are described.

Key words Visual acuity; optotype charts; luminance; contrast; forced choice; logMAR.

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Acknowledgements:
We would like to thank Mr. Vito Pasceri and Mrs. Cristina Chini for the technical support furnished in the graphic realization of the charts. Particular thanks are due to Mrs. Christine Di Salle for the competence and the patience with which she has taken care of the English translation of the manuscript. This research was developed within the targeted project FATMA (Prevention and Control of Risk Factors), sub-project Community Medicine, of the CNR (Italian National Research Council), 1990-1995, Grant no. 9100119.PF41.

Introduction The measurement of visual acuity (V.A.) is an essential part of the ophthalmologic examination and it represents the most common and useful test for assessing visual function. Although we usually think of the V.A. as a measure of the resolving power of the foveal area, assessment of abnormal visual function may be related to different conditions such as refractive errors, media opacities, and retinal and optic pathway diseases.

The specific need for standards is related to the type of use to which the test is designed. The common aim is to compare repeated measurements made by more than one examiner in different places.[1]

Thus, in clinical practice, the primary need is to compare the results to evaluate the occurrence or the evolution of pathology; in clinical trials or research projects, the need is to perform a reliable and reproducible measure; in qualifying tests (physical standards) the need is to employ univocal judgement criteria.

A recent paper[2] summarizes the recommended procedures for the standardized measure of V.A. evolved as part of 20 years of clinical research.

The aim of the present work is to provide not only a guideline, but also a review of the main arguments related to the standardized assessment of V.A. Furthermore, we propose new standard V.A. test charts designed by following the basic recommendations of the National Academy of Sciences – National Research Council (NAS-NRC);[1] the validation and comparison of the new test charts with the current standard charts are reported elsewhere (in process of publication).

Standardization of V.A. measurement is a global procedure that involves different aspects such as the characteristics of the test devices, the notation employed in recording the acuity level and the strategy for absolute threshold assessment. In the present paper our attention will be restricted to the "recognition acuity" (Minimum legible).

Characteristics of the test devices

"DISTANCE ACUITY TEST"

Standard optotypes The Landolt broken rings are widely accepted as the standard of reference.[3] The use of other optotypes requires a demonstrable equivalence to Landolt rings and an equal recognition difficulty. Both Sloan[4] and British Standard Institution[5] optotype sets show these features.[6-8] (Fig. 1)

Optotypes scaling Optotype sizes must be reduced in a constant way in order to obtain an equal variation all over the scale extension.[9] A logarithmic progression in steps of 0.1 logUnits corresponds to a geometric progression in which each row contains optotypes about 1.26 times smaller than the preceding one. The V.A. threshold is obviously affected by the rate of scaling employed.

Scale extension A useful scale extension spans at least from 10 to 0.8 minutes of arc of MAR of stroke, at the full test distance.[2,10]

Optotypes spacing Optotypes must be quite far apart to avoid the «crowding effect».[11,12] If this distance is at least 5 times their visual angle, the acuity may be assumed equal to that measured with isolated characters («Interaction free acuity»). Because the strength of the crowding effect varies as a function of the distance between the optotypes, V.A. measurements performed by means of non-homogeneous charts may lead to very different results.[8]

Number of optotypes NAS-NRC recommended ten optotypes divided into two rows of five; eight letters per row is the minimum accepted. The same number of letters at each size level is required.[1]

Background luminance In the normally sighted, V.A. increases as a function of the background luminance from mesopic to high photopic luminance until glaring brightness is obtained and V.A. begins to decrease.[13] The V.A. increase spans from 0.025 cd/m² to 60 cd/m². Above 80 cd/m² the variation is very slight and above 500 cd/m² it is quite negligible.[14] This

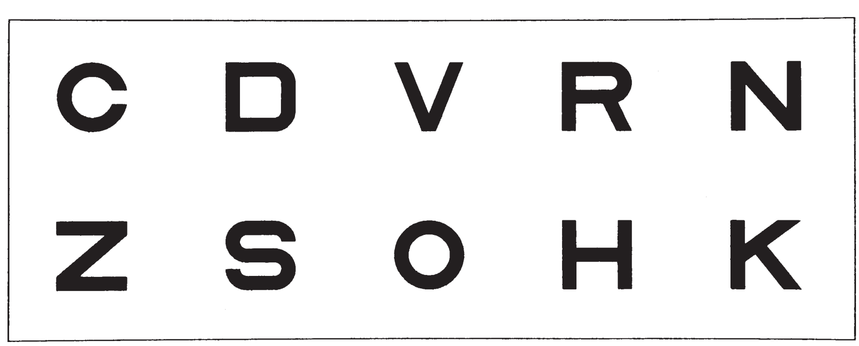

Fig. 1. Sloan optotypes. These letters are substantially equivalent to Landolt rings in terms of recognition difficulty.

effect is related to the improvement of contrast sensitivity at high levels of luminance.[15]

Ambient luminance Maximal V.A. is achieved under photopic conditions. It has been demonstrated that if the contrast and the luminance of the test target are kept constant, the V.A. varies with the retinal adaptation conditions. In photopic adaptation the V.A. increases with the target luminance. In scotopic or mesopic adaptation the peak levels of V.A. are relatively smaller.[16] It is advisable to avoid V.A. measurement in a dark room, but ambient luminance should not exceed one half of the chart background luminance.[1]

Light wavelength A change in wavelength of the background light source leads to image defocusing that, under dynamic conditions, produces a variation in amount of accommodation. In the presence of achromatic light such as daylight (CIE Source 6500), incandescent lights (CIE Source A) and fluorescent tubes, it is possible to assess the wavelength for which the eye must be focused to obtain minimum blur, as well as the relative amount of defocusing for different sources.[1] The spectral centroid of a source may be assumed to correspond to the wavelength for which the eye must be focused.[17] This is also true for fluorescent sources in spite of the continuous emission spectrum.[18] Assuming that the human eye is in focus at the wavelength of sodium emission (589 nm), to get a defocusing of 0.25 diopters it requires a wavelength shift of 45 nm. Light sources of which the spectral centroid falls in this range (589-544 nm) are useful for the background illumination of standardized charts.[1]

Optotypes contrast The ability to identify an optotype is not only related to its angular width but also to the test target contrast. V.A. (resolution or recognition) is reduced as the contrast between the test target and the background decreases. When the contrast is reduced below a critical value (threshold) the ability to resolve the target fails.[19-21] The maximal V.A. is achieved when the contrast between optotypes and background is above 80%.

Test distance Changes in test distance under dynamic conditions alter the focus and then the related amount of accommodation. V.A. measurement performed at different distances may be affected by this factor. The standard chart testing distance should be 4 meters; the choice of this distance is supported by several arguments:

- easy approximation to infinity by adding algebraically –0.25 D to the refractive correction.
- easy conversion of the Snellen ratio between 4 meters and 20 feet
- maximal acuity and minimal dispersion of acuity scores at distances close to 4 meters.[1,22,23]

"NEAR ACUITY TEST" To provide V.A. measures comparable to those performed at four meters, the near charts should meet the same specifications as outlined for the distance charts. Under these conditions, in a large majority of patients, the near and distance V.A. threshold expressed as logMAR will

#	S	O	C	D	K	V	R	H	N	Z
%	70.6	71.0	71.4	79.5	82.1	84.6	86.3	89.3	91.6	94.0

TABLE 1. Degree of difficulty of Sloan letters (% corrected at threshold)

agree within 0.1 logUnits. Differences in distance and near test occur in cataract patients where the distance acuity is generally lower than the near one. Retinal and optic pathway diseases usually reduce both distance and near acuity to the same degree.[1]

Characteristics and limits of the current distance charts

THE SNELLEN CHART This is one of the most widely used charts for V.A. testing. In spite of its wide diffusion the chart organization shows several limitations for standard measurements[7,24,25]:

- the different numbers of optotypes per row; as a result, the difficulty of the task increases as the optotypes become smaller.
- the irregular progression in letter size; the scale of the measure is not the same over the entire extension of the chart, so that the gain or loss of one line does not have the same value in different parts of the chart.
- the differences in the recognition difficulty of the optotypes; the chart includes both relatively easy letters such as A and L, and more difficult ones such as B, E and F.
- the difference in background luminance related to different chart manufacturers.

THE ETDRS CHART This represents the major effort to introduce a standardized chart based on the recommendations of NAS-NRC. The chart introduced by Ferris,[7] which modifies the Bailey & Lovie chart,[26] shows five Sloan optotypes per row and a regular progression of the type size and spacing, following a logarithmic scale in steps of 0.1 logUnits.[3] The use of five letters per line necessitated a choice of a combination of Sloan optotypes in order to obtain the same mean difficulty for each line (see Table 1). The authors point out that the use of 5 letters per row is the only deviation from the NAS-NRC recommendation. The reduced number of optotypes increases the probability of false recognition due to guessing driven by the forced choice method.[27]

The background luminance is about 150 cd/m^2 and thus exceeds the limit of 85 ± 5 cd/m^2 without any possibility of regulation. However, this feature does not affect the final results of the measure, and other authorities have suggested a standard background luminance ranging from 120 to 300 cd/m^2.[5,28]

Characteristics and limits of the current near charts

The first problem in establishing near test standards is if it is better to use a text-reading task rather than optotypes recognition. Text reading is qualitatively different from recognition of individual optotypes, with little or

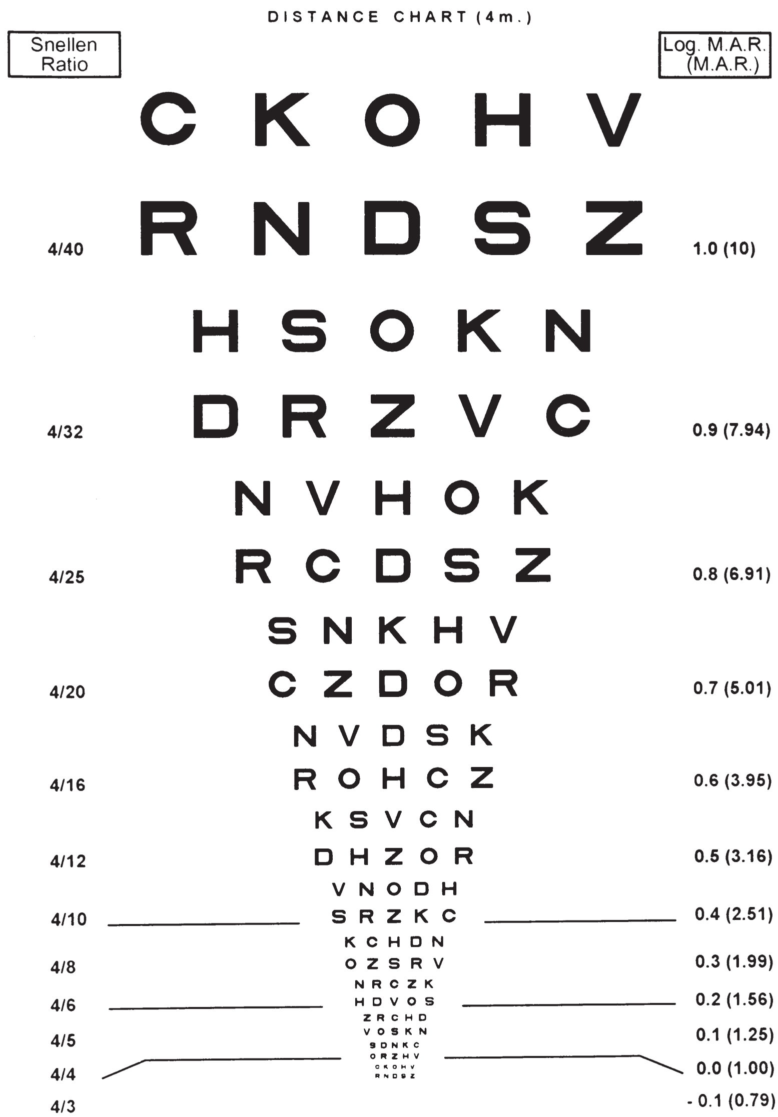

Fig. 2. Ten-letter chart (Distance acuity test).

TABLE 2. Distance test, 4 m (20 ft) – Conversion table (sizes in steps of 0.1 logUnit)

Snellen Ratio			*Decimal Acuity*	*M.A.R.*	*logM.A.R.*	*Stroke Size*	*Optotype Size*	*Relative Size*
4 m.	*20 ft.*	*Decimal ratio*		*min. of arc*	*log Unit*	*mm.*	*mm.*	×
4/40	20/200	1/10	0.10	10	1.0	11.64	58.20	40
4/32	20/160	1.2/10	0.12	7.94	0.9	9.24	46.23	32
4/25	20/125	1.6/10	0.16	6.31	0.8	7.34	36.72	25
4/20	20/100	2/10	0.20	5.01	0.7	5.83	29.17	20
4/16	20/80	2.5/10	0.25	3.98	0.6	4.63	23.17	16
4/12.6	20/63	3.2/10	0.32	3.16	0.5	3.68	18.40	12.6
4/10	20/50	4/10	0.40	2.51	0.4	2.92	14.62	10
4/8	20/40	5/10	0.50	1.99	0.3	2.32	11.61	8
4/6.3	20/32	6.5/10	0.65	1.58	0.2	1.84	9.22	6.3
4/5	20/25	8/10	0.80	1.25	0.1	1.47	7.33	5
4/4	20/20	10/10	1.00	1	0.0	1.16	5.82	4
4/3.2	20/16	12/10	1.20	0.79	–0.1	0.92	4.62	3.2

no correlation between the two tests. Consequently, text-based testing is more appropriately used in the evaluation of visual impairment rather than in V.A. measurement.[4,29-31]

Many optotypes-based systems have been proposed, most of which have many flaws. In fact both the "Jaeger system" and the "point system" can vary across different manufacturers of the test card, and thus, in spite of their diffusion, they are not useful in the standardized assessment of V.A.[32,33]

- Snellen near test charts show the characteristics and limits of the distance chart previously discussed.
- The ETDRS near test is a 1:10 scaled-down copy of the distance test chart and shows the characteristics and limits of the distance chart.

Is there room for new charts for visual acuity measurement? We have designed new visual charts (see Fig. 2 and Table 2) that tend to follow strictly the NAS-NRC standardization guidelines,[1] with the aim of improving the ETDRS charts.[34] The characteristics of the distance test chart are summarized below:

• Distance testing:	4 meters
• Optotypes:	Sloan Letters (**C D K H N Z R S V O**)
• Specification of acuity:	MAR/logMAR/Snellen Ratio
• Variation of the size:	Steps of 0.1 logUnits
• Horizontal spacing:	Equal to the optotype size
• Vertical spacing:	Equal to the size of the preceding line
• Number of optotypes:	Ten letters divided into two rows of five
• Contrast:	> 85%
• Background luminance:	From 100 to 500 cd/m²
• Scale extension:	From 1 to -0.1 logMAR

The *Near test chart* is a 1:10 scaled-down chart. The test distance is thus 40 cm. The scale extension spans from 1.4 logMAR (4/100) to –0.1 logMAR (4/3) at full distance (see Fig. 3 and Table 3). The main differences with respect to ETDRS charts are:

- the presence of all ten Sloan optotypes per angular width arranged in two rows of five;
- background luminance variable from 100 to 500 cd/m² (distance charts);
- wider extension of the scale in the near test until 1.4 logMAR (4/100); this permits one to evaluate low levels of acuity at a standard distance of 40 cm (2.5 D) rather than at 20 cm (5 D) as needed using ETDRS near charts.

Notation employed in recording the V.A. level

DISTANCE CHARTS

• *Snellen acuity* This is the most widely used notation format in all English-speaking countries. It is based on the assumption that a subject with normal recognition acuity can resolve an optotype with a visual angle of 5′ and a resolution angle (stroke) of 1′ (minute of arc). The V.A. level is expressed as the ratio between the reading distance and the distance in meters at which the stroke width of the equivalent Landolt ring subtends 1 minute of arc:

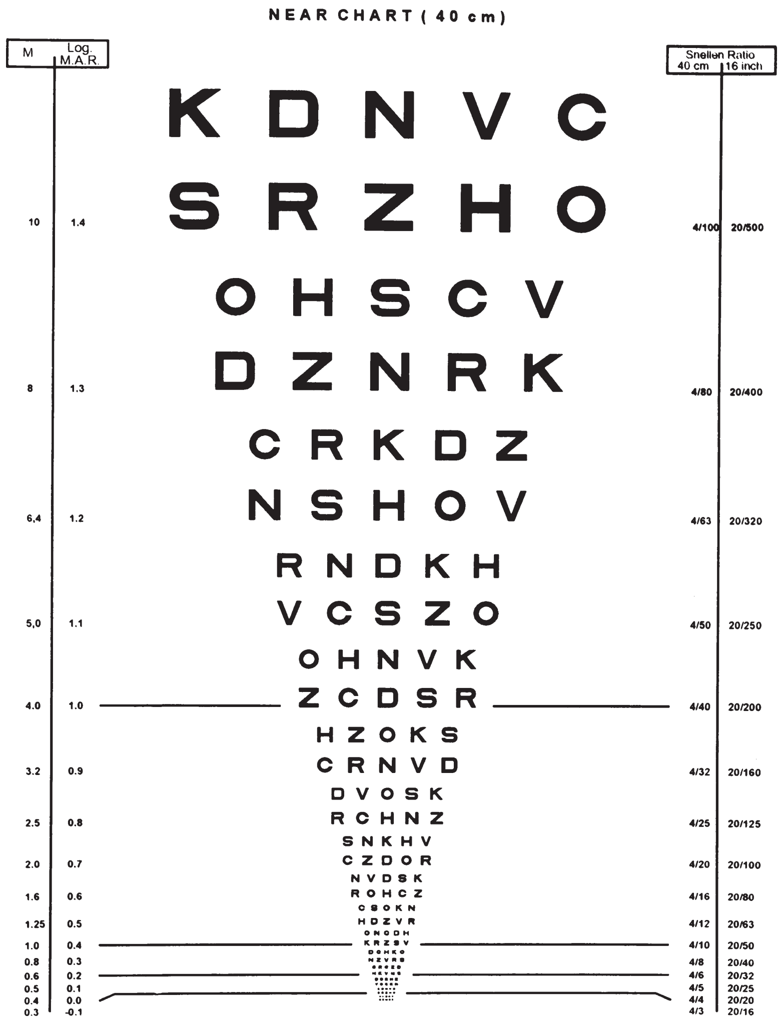

Fig. 3. Ten-letter chart (Near acuity test).

TABLE 3. Near chart, 40 cm (16 inch). Conversion Table (sizes in steps of 0.1 logUnit)

Equivalent Snellen Ratio	*Snellen Ratio (centimeters)*	*Snellen ratio (inches)*	*Decimal acuity*	*Log.MAR*	*Sloan M system*
4/100	40/1000	20/500	0.04	1.4	10
4/80	40/800	20/400	0.05	1.3	8.0
4/60	40/600	20/300	0.06	1.2	6.4
4/50	40/500	20/250	0.08	1.1	5.0
4/40	40/400	20/200	0.10	1.0	4.0
4/30	40/300	20/150	0.13	0.9	3.2
4/25	40/250	20/125	0.15	0.8	2.5
4/20	40/200	20/100	0.20	0.7	2.0
4/16	40/160	20/80	0.25	0.6	1.6
4/12	40/120	20/60	0.30	0.5	1.25
4/10	40/100	20/50	0.40	0.4	1.0
4/8	40/80	20/40	0.50	0.3	0.8
4/6	40/60	20/30	0.65	0.2	0.6
4/5	40/50	20/25	0.80	0.1	0.5
4/4	40/40	20/20	1.00	0.0	0.4
4/3	40/30	20/15	1.30	-0.1	0.3

V.A. = m/M

In Europe there is a strong tendency to convert the Snellen ratio to the decimal system (decimal acuity).[35] In Italy, a further approximation is carried out by transforming the decimal acuity into a decimal ratio, where 10/10 means 6/6 or 5/5 or 4/4 or 3/3 acuity, and 1/10 means 6/60 or 5/50, etc. Both the decimal acuity and the decimal ratio allow direct comparison of V.A. results performed by means of 3, 4, 5 and 6-meter charts, but they represent an improper use of the Snellen ratio.[36] Decimal acuity may be confused with both the Snellen Sterling "percentage of visual efficiency", which has a very different meaning, and the MAR values.[15,37]

• *Minimum Angle of Resolution (M.A.R.)* The V.A. threshold may be expressed in terms of the minimum angle of resolution of the optotypes stroke. The advantages of this kind of format include:[38]
– It states the V.A. in absolute terms
– It does not involve any assumption of normal reference values
– It can be used with charts of any letter size progression
– It allows direct comparison of values obtained with different distance charts
– It allows direct comparison between distance and near acuity levels
– It allows easy conversion from and to the Snellen notation
– It is expressed as an internationally used unit of measurement and is therefore useful in defining an international standard.

• The *Logarithm of the Minimum Angle of Resolution (logMAR)* is the common logarithm of the minimum angle of resolution and allows a fast and easy V.A. specification.[1,6,26] This notation has further advantages in comparison to the MAR notation, such as:
– Easy progression in steps of 0.1, from +1 to –0.1 (–0.2) (see Tables 2 and 3)
– The ability to express V.A. as an interpolated value.[6,39]

NEAR CHARTS

• The *Snellen acuity* should be expressed as the ratio between the test distance in centimeters (c) and the distance in centimeters at which the stroke of the equivalent Landolt C ring subtends 1 minute of arc (**C**):

V.A. = c/C

The *MAR and logMAR notations* are equivalent in both distance and near tests and allow direct comparison between the distance and near acuity levels.

• The *Sloan M system*, although designed for specifying continuous text reading, can be extended to individual letter near charts. An 1-M letter is defined as an optotype whose height subtends a visual angle of 5 at a

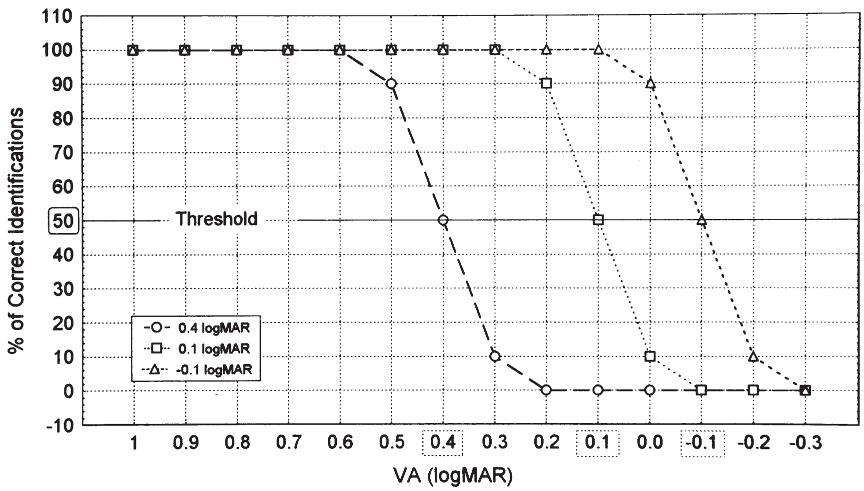

Fig. 4. The plot shows the recognition threshold in logmar of three patients with different levels of V.A. The absolute threshold is defined statistically as the boundary stimulus at which just more than 50% of the presentations are recognized.

distance of one meter. Comparison with other notations is not easy and the use of a conversion table is useful (see Table 3).[40]

Standard procedures for V.A. assessment

FORCED CHOICE The general purpose of this psychophysical method is the measurement of the threshold. This term refers to a boundary stimulus that results in a change from sensation to no sensation. When we evaluate the V.A. level we detect the minimum width of the stroke expressed in minutes of arc that allows the correct identification of the test (absolute threshold).[41] The threshold is defined statistically as the boundary stimulus at which more than 50% of the number of presentations is recognized (see Fig.4).

Subjects with the same recognition acuity may show different results in V.A. testing in accordance with the ability to answer when tested with the threshold stimuli. The forced choice procedure can limit differences related to the individual response bias or criterion.[42] This method requires that the percentage of identifications be corrected for guessing. The following relation, called the Abbot formula, permits one to correct the number of identifications for guessing:[43,44]

$$\mathbf{CI} = \frac{N(n-1) - Mn}{N(n-1)}$$

In this formula, **CI** is the percentage of correct identifications, **n** is the number of optotypes per row, **N** is the number of presentations and **M** is the number of mistakes. Table 4 shows the percentages of correct identifications calculated under different test conditions.

STATING THE EXAM END POINT There is a close relationship between the V.A. threshold and the criteria used to evaluate subject performance in reading an eye chart. The plot of a frequency seeing curve indicates that the V.A. threshold varies according to the percentage of correct responses assumed as the end point (see Fig. 5).

TABLE 4. Percentage of the identifications corrected for guessing by means of the Abbott Formula.

Number of optotypes (n)	*Number of presentations (N)*	*Number of Mistakes (M)*	*% of identifications (I)*	*% of correct identifications (CI)*
4	4	1	75%	66%
4	5	1	80%	73%
4	6	2	60%	46%
4	7	2	71%	62%
10	5	2	60%	55%
10	7	2	71%	68%

The ophthalmic literature shows different criteria for measuring the V.A. threshold. Most authors commonly use the correct identification of 50%+1 of the characters of a defined line on a Snellen chart as the end point. This criterion was employed in the Framingham Eye Study.[45] Ferris suggested the identification of 4 out of the 5 characters per line in charts arranged in a logarithmic scale.[7] Wong & Kaye[46] suggested, for purposes of V.A. screening, the correct identification of 100% of the characters in charts arranged with 2 letters per row and especially designed for quick tests. The standard recommended by NAS-NRC is the correct identification of 50%+2 of the characters on charts with 10 optotypes per row. Under these conditions the probability of guessing 7 out of 10 letters correctly is less than 1% and thus the measurement of the V.A. threshold is highly significant.[1]

The LogMAR notation allows the V.A. level to be expressed in terms of interpolated values. To each optotype we can assign a score that is equal to the value of the logarithmic progression (0.1) divided by the number of optotypes per angular width. In a ten-letter chart this value is 0.01(0.1/10) per recognized optotype. If a patient can read 7 out of 10 letters of the row corresponding to 0.0 LogMAR and two letters of the next –0.1 line, we can interpolate a V.A. score by subtracting 0.01 per recognized letter in the next row. In this example, the visual acuity is "V.A. = 0.0 – 2 × 0.01 = -0.02", which represents a score interpolated between 0.0 and –0.1 logmar.

The acuity score may be useful both for detecting subtle changes in V.A. and for carrying out accurate statistical tests.[7]

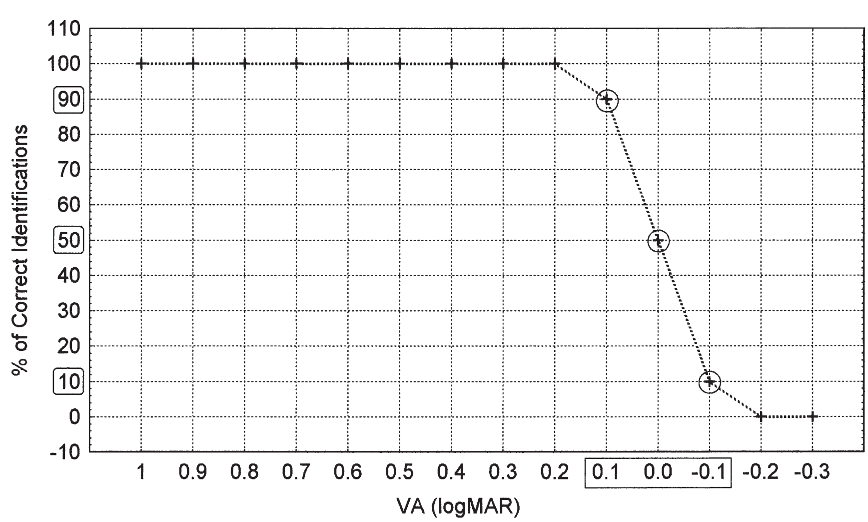

Fig. 5. The plot of a frequency seeing curve indicates that the V.A. threshold varies according to the end point definition. The V.A. is 0.1 logmar if we assume 90% of correct identifications as the end point, 0.0 logmar for 50% and -0.1 for 10%.

Distance (meters)	Log .M.A.R.	Snellen ratio 4 meters	20 feet	Decimal ratio
4	1	4/40	20/200	1/10
3,2	1.1	4/50	20/250	1/12
2,5	1.2	4/63	20/320	1/16
2,0	1.3	4/80	20/400	1/20
1,6	1.4	4/100	20/500	1/25
1,3	1.5	4/125	20/630	1/30
1,0	1.6	4/160	20/800	1/40
0,8	1.7	4/200	20/1000	1/50
0,6	1.8	4/250	20/1250	1/62
0,5	1.9	4/320	20/1600	1/80
0,4	2.0	4/400	20/2000	1/100

TABLE 5. Conversion table logmar/ Snellen ratio at low V.A.

STANDARD METHODS FOR MEASURING LOW V.A. A drop in the V.A. below 4/40 requires that V.A. testing be performed at a closer distance than the standard one. With a 4-meter logarithmic chart we can follow two procedures, depending on the format of the notation employed:

1) If we use the MAR notation or the Snellen ratio, when we reduce the test distance by half we double the MAR resolution or double the denominator of the Snellen Ratio. Thus, 4/40 at 4 meters = 4/80 at 2 meters = 4/160 at one meter, etc.

2) If we use the logMAR format we have to reduce the test distance in steps of 0.1 logUnits (4 – 3.2 – 2.5 – 2.0 – 1.3 and 1). Each reduction step corresponds to a variation of +0.1 log Unit on the chart scale. Identification of the first line corresponds to a V.A. of +1.0 logmar at 4 meters, +1.1 LogMAR at 3.2 meters, +1.2 LogMAR at 2.5 meters, etc. (see Table 5 and Fig. 6).

DIFFERENT CHARTS FOR REFRACTION AND V.A. MEASUREMENTS In order to avoid memorization of the sequence of the optotypes it is strongly recommended to employ at least 3 different charts to perform the distance

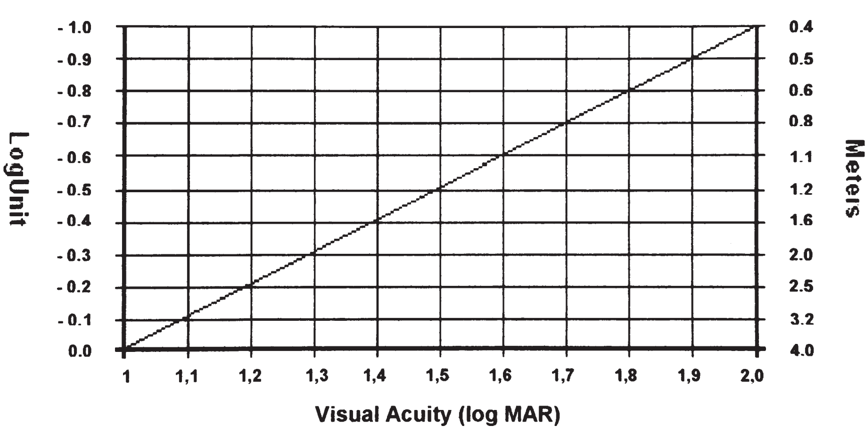

Fig. 6. Due to the increase in the angle of resolution, the reduction of the test distance in logarithmic steps corresponds to a variation of +0.1 logUnit of V.A. on the chart scale. Correct identification of the first line at 4 meters corresponds to a V.A. of +1.0 logmar, at 3.2 meters +1.1 logmar, at 2.5 meters 1.2 logmar, etc. See also Table 5.

acuity test. The first chart must be used only for refraction, the second for V.A. assessment in the right eye and the third for the left eye. Likewise, near acuity must be measured with different charts for each eye. A lighting device is needed that allows measurement at the same background luminance employed in the distance test.

Discussion The Snellen chart, in spite of its diffusion, presents too many flaws to to be used as a reference. Charts with a regular progression of optotype size and spacing, with the same number of letters per row of approximately equal recognition difficulty (Landolt C or Sloan letters), are more useful for the standardization requirements.

V.A. testing is currently employed for different purposes, ranging from the assessment of refraction to the evaluation of visual function. Wong & Kaye[46] suggested that different charts may be useful in relation to specific needs, and each chart should balance sensitivity, specificity and the desired examination time.

Highly sensitive test charts produce a low percentage of false negatives, while highly specific tests produce few false positive responses. The sensitivity of the chart is related both to the number of letters per row and the requested number of correct identifications for V.A. threshold assessment. The specificity of the test may be reduced by difficult and time-consuming examinations.

A two-letter chart combined with a suprathreshold end point may be useful in V.A. screening, while large epidemiological population studies may benefit from more balanced tests such as ETDRS five-letter charts.[7]

Nevertheless, in other studies, such as refractive surgery trials, cataract medical treatment trials, etc., it may be relevant to measure the V.A. threshold or score in order to analyze small differences over time. In these cases, the use of the described ten-letter chart may permit the use of more sensitive and specific tests.

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