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LOW VISION

Resolving the clinical acuity categories "hand motion" and "counting fingers" using the Freiburg Visual Acuity Test (FrACT)

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Abstract
Purpose The Freiburg Visual Acuity Test (FrACT) has been suggested as a promising test for quantifying the visual acuity (VA) of patients with very low vision, a condition often classified using the semi-quantitative clinical scale "counting fingers" (CF), "hand motion" (HM), "light perception" (LP) and "no light perception". The present study was designed to assess FrACT performance in a sizable number of CF, HM, and LP patients in order to generate a setting for future clinical studies in the low vision range.
Methods We examined a total of 41 patients (LP, $n=11$; CF, $n=15$; HM, $n=15$) with various eye diseases (e.g., diabetic retinopathy, ARMD), covering the clinical VA scale from LP to CF. The FrACT optotypes were presented at a distance of 50 cm on a 17-inch LCD monitor with four random orientations. After training, two FrACT measurements (test and retest) were taken, each comprising 30 trials.
Results FrACT measures reproducibly the VA of CF and HM patients. In CF patients, FrACT resulted in a mean logMAR=1.98±0.24 (corresponding to a decimal VA of 0.010), for HM in a mean logMAR=2.28±0.15 (corresponding to a decimal VA of 0.0052). In all LP patients the FrACT values were close to what would be obtained by random guessing. The mean test–retest 95% confidence interval was 0.21 logMAR for CF patients and 0.31 logMAR for HM respectively. Test-retest variability declined from 24 to 30 trials, showing that at least 30 trials are necessary.
Conclusion FrACT can reproducibly quantify VA in the CF and HM range. We observed a floor effect for LP, and it was not quantifiable further. Quantitative VA measures are thus obtainable in the very low-vision range using FrACT.

Keywords Visual acuity · Low-vision assessment · Psychophysics

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Introduction

Visual acuity (VA) is one of the most important ophthalmological parameters in clinical studies. VA in the low-vision range is clinically assessed with the categories "counting fingers" (CF), "hand motion" (HM), "light perception" (LP) and "no light perception"; a scale that is only semi-quantitative and does not permit differentiation within those categories.

Quantitative VA tests used in clinical studies—such as the Early Treatment Diabetic Retinopathy Study (ETDRS [1, 11])—only cover VA ranges down to CF [7, 14]. The values below the testing range of the ETDRS charts have been approximated, e.g., by using the Snellen charts [12, 13]. Holladay [13] estimated a $VA_{decimal}$ of 0.01 for CF and 0.001 for HM, whereas Grover et al. [12] estimated a $VA_{decimal}$ of 0.0025 for CF, 0.002 for HM, 0.0016 for LP, and 0.0013 for blindness. These estimates do not allow further differentiation of VA within the CF, HM and LP groups. It may, however, be important to detect minor differences within these categories in order to monitor

progress or disease remission, especially under therapy regimes. Because of new potential therapeutic interventions, e.g., in the field of retinology, it is mandatory to quantitatively assess the VA in patients with very low vision as well.

The Freiburg Visual Acuity Test (FrACT) was first described in 1996 [3], and has since been used and validated by several authors [6, 16, 17, 19]. FrACT yields results that concur closely with those obtained by traditional clinical eye charts (Snellen) [3] and by the ETDRS charts [17]. The test automatically presents single optotypes at appropriate sizes to home in on the threshold following the best-PEST algorithm (best parameter estimation by sequential testing) [15]. The patients can pace the test themselves using a response box, which saves time, especially for repeat visits. In this context, one main advantage of FrACT is that optotypes can be presented in very large sizes, limited only by the computer screen. A previous study from this laboratory showed in a small number of patients that FrACT obtained results with acceptable test-retest reproducibility for acuities down to HM [17].

The purpose of this study was twofold:

1) To verify FrACT's reliability in the very low vision range (CF, HM and LP) with a higher number of patients (20 with CF and below in [17], 41 additional patients here).
2) To evaluate the feasibility of a shortened test using fewer trials, which would be desirable especially in elderly and frail patients.

Material and methods

Patients

We examined 41 eyes of 41 patients with low vision of CF and below; their age ranged from 20 to 90 years, averaging 65±17.5 years. Underlying diseases involved optical, central and diffuse retinal problems and optic nerve affections (Table 1).

The patients' visual status was stratified into three groups using a clinical scale: (1) CF (n=15), (2) HM (n=15) and (3) LP (n=11) at a testing distance of 30 cm. The tenets of the Declaration of Helsinki were followed [20], the study protocol was approved by the local ethics committee and informed consent obtained from all participating patients.

Table 1 Clinical disease categories of the 41 participating patients

Disease category	*N*
Corneal diseases	9
Trauma	7
Retinal detachment	6
Cataract	4
Age-related macular degeneration	3
Glaucoma	3
Macular hole	3
Diabetic retinopathy	2
Marfan's syndrome with dislocated lens	1
Optic nerve atrophy	1
Retinal vascular occlusion with macular edema	1
Uveitis	1

The Freiburg Visual Acuity Test (FrACT)

FrACT is a computerized VA test capable of presenting very large Landolt-C optotypes with randomized gap orientations on a computer monitor. This test has been developed and described in detail by Bach [3, 6] and runs on the Macintosh, Linux or Windows operating systems. It has been validated in various studies [10, 16, 17, 19] and can be downloaded free of charge [5]. Apart from a computer, appropriate monitor and keyboard, no additional equipment is needed. FrACT can be calibrated easily to the monitor size and its spatial resolution. In this study, the optotypes were presented on a 17-inch LCD monitor (luminance 170 cd/m^2, resolution 1280×1024 pixel) and patients were tested at a distance of 0.5 m. The orientation of the Landolt-C was random for every trial, whereas the size of each optotype presented always targets the currently most probable VA threshold, calculated on the basis of all previous responses following the best-PEST algorithm [15, 18]. The algorithm operates on a log(VA) scale; step sizes thus automatically take the logarithmic progression of VA into account [log(VA) = –logMAR]. The steps are calculated by an adaptive-staircase procedure [15, 18]. Consequently, step sizes are initially quite large (equivalent to approximately 3 lines), but become smaller than 1 line when the algorithm homes in on the VA threshold. As pixel size artifacts limit the presentation of very small stimuli, spatial resolution was improved by a factor of four over the pixel size by using an anti-aliasing algorithm (smoothing of contours by multiple gray levels [4]). While this is relevant for assessing VA in the normal range, it is not in low vision, because there the limitation is the monitor's total size and not its pixel size. The test is terminated after a pre-set number of trials (e.g., 30), the optimal number of presentations being one issue of this study. More details on the maximum likelihood-based threshold estimation are given in [3, 6]; examples of the probability density maps are presented in [6], showing very little effect of slope on threshold estimation. Additional details are given in the manual, available at <michaelbach.de/fract/>, where also the FrACT program is offered as a free download.

Procedure

All VA measurements were taken according to the same protocol. Before the main testing procedure, the standard clinical VA was determined for each subject using the semiquantitative ordinal values CF, HM, and LP at a distance of 30 cm. Patients' correction was based on the results of automatic refractometry. All subjects wore additional correction for the particular testing distance. After binocular training, the fellow eye was occluded. All VA tests were performed in a dimly lit room; illumination measured at the subject's eye was 50 lux. The FrACT optotypes were presented on the monitor at a distance of 50 cm, a custom measuring cord ensured a correct and stable testing distance. Landolt-C optotypes were displayed in one of four orientations at highest contrast (around 97%). Although FrACT can optionally display Landolt rings in eight different gap positions, we presented only four non-oblique positions in this study, because previous experience had shown this to be less confusing for elderly patients and those with very low vision. The operation of the response box by the patients themselves often proved difficult, so the examiner operated it. During the training phase, the examiner evaluated the patient's behavior. When right–left confounds were observed, the patient was instructed to point in the perceived direction. Only one Landolt ring was displayed at a time, and the subjects' verbal response was entered into the computer by the examiner. When the optotypes became so small that they were in the threshold region of the psychometric acuity function, patients typically reported "I'm not sure" or "I can't see anything." However, to avoid bias by the "subject's criterion" (a term from signal detection theory), we used the forced-choice procedure, i.e., the patients always had to report a gap direction, even if based on "best guess". This required gentle coaxing in the training phase.

The first presented value of $VA_{logMAR} = 1.0$ ($\triangleq VA_{decimal} = 0.1$) is not recognizable for our low-acuity patients. If the patient accidentally responds with the correct orientation, a lengthy and frustrating run of initially rather small optotypes would ensue. To avoid this, the operator immediately entered an incorrect response for the first trial. The next one is a much larger optotype in the low-acuity range. Thus the first trial is used to rapidly move FrACT into the very low acuity range.

Decimal visual acuity is defined as the reciprocal value of the gap size (in minutes of arc) of the smallest recognized Landolt-C. Using FrACT, this is usually the value obtained after the 29th trial, the last trial being a "bonus trial". (Bonus trials present optotypes three times larger than the current threshold estimate, thus making them easy to recognize and helping to keep the subjects happy; in Fig. 1 they are obvious as seeming outliers [3].) Figure 1 clarifies the method's principle, showing how the presented Landolt-C sizes converge to the final value. Also, for every run comprising 30 trials we recorded the following parameters per trial: the Landolt-C gap sizes, gap orientation presented, gap orientation indicated by the patient, and reaction time. This was possible thanks to FrACT's "export to clipboard" option (see manual [5]). The final result was presented on the screen, in either Snellen format or decimal notation.

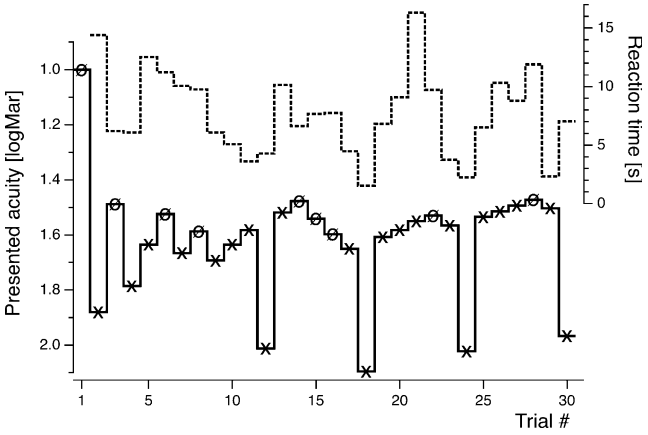

Fig. 1 Representative run of FrACT in a CF-category patient. Thirty consecutive values of Landolt-C gap size (*lower line*); "*x*" indicates correct, "*Ø*" incorrect responses. It is apparent that the optotype size converges on the final value; the 4 "bonus trials" at trial #12, 18, 24 and 30 are also obvious. Reaction time roughly indicates difficulty of the decision

Statistical analysis

All statistical evaluations were performed on the approximately normally distributed logMAR scale. The 95% confidence interval of the test-retest difference was used to quantify FrACT's test-retest reproducibility, for the full run (30 trials) and for intermediate results after 12, 18 and 24 trials. For intuitive display for some regions of the world, all results were also transformed back to the decimal VA scale: $VA_{decimal} = 10^{-logMAR}$.

Results

Values and reproducibility of FrACT measurements

The mean values obtained for the three acuity categories are illustrated in Table 2. The "*n*" refers to the number of eyes = the number of patients; the result values are the mean across two measurements per eye. No successful measurement was possible with FrACT for LP (n=11), because nine of the 11 LP-eyes attained a mean VA_{logMAR} = 2.6 which corresponds to the maximum possible Landolt-C size. This value results when responses are nothing but

Table 2 Results details per acuity category

Acuity category	*N*	VA [logMAR] (mean ± SD)	VA [decimal] (mean, 16% ... 84% quantile	Test-retest 95% confidence interval [logMAR]	Mean total duration [mins]
CF	15	1.98±0.24	0.010, 0.006 ... 0.018	0.21	3.7±1.3
HM	15	2.28±0.15	0.0052, 0.037 ... 0.074	0.31	4.7±2.4
LP	11	–	–	–	5.6±3.7

The mean VA results were obtained by first averaging the two runs, and then calculating the mean and standard deviation across eyes, all in logMAR units. Since decimal VA is not distributed normally, the resulting ±SD values are given as the 16% and 84% quantiles)

random guessing. To assess variability, we calculated the 95% confidence interval of the test–retest difference; it is also given per acuity group in Table 2.

FrACT's reproducibility is graphically demonstrated in Fig. 2. VAs of the first test are plotted versus those of the second test (re-test). The nine out of 11 patients whose test resulted in the largest possible Landolt-C size, are indicated by the horizontal bar on the bottom left. All other patients' values are close to the 45° line. On average, they are a little above, which probably indicates a learning effect.

FrACT test duration

The total mean times per run [minutes] given in Table 2 are analyzed in greater detail in Fig. 3, which illustrates the test duration and reaction times: The poorer the vision, the longer the test duration. The mean duration of the test in the LP group was 5.6±3.7 min (mean±SD). Corresponding values for the HM group were 4.7±2.4 min, and for the CF group 3.7±1.3 min. Analysis of the patients' waiting time before making a choice revealed that the CF and HM groups' reaction times were shorter with correct than with incorrect responses. On the other hand, the LP group's reactions were nearly identical across all conditions, indicating that the patients merely guessed the gap's orientation for all sizes of the Landolt ring.

When comparing reaction times for test 1 versus test 2, we found they decreased on average down to 87% (p=.015, paired t-test). This decrease held across all acuity categories, and was less obvious for the bonus trials.

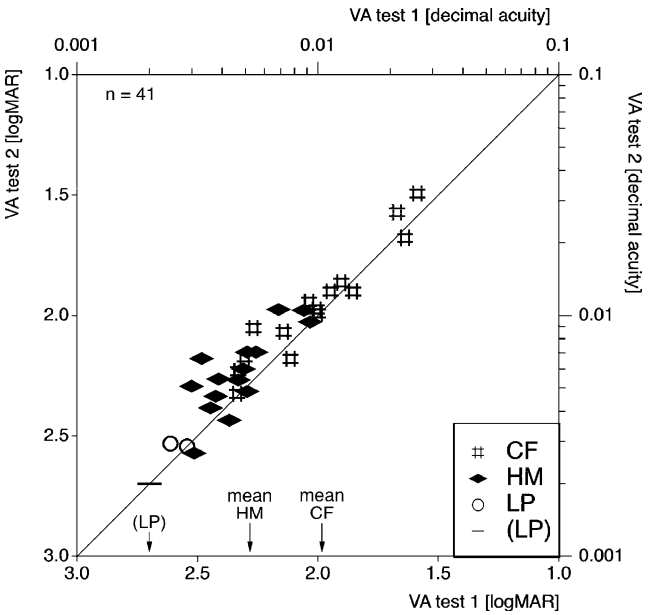

Fig. 2 Test-retest reproducibility. Categories LP, HM and CF are represented with different symbols. *Arrows* point to average values of the three categories. In nine LP patients FrACT resulted in the lowest possible value, as indicated by the *horizontal bar* and *LP in parentheses*, two LP patients with higher acuity by *circles*. More values are located above the diagonal, indicating a learning effect. Reproducibility is high, even for the two LP eyes without floor effect. VA values rise from LP over HM to CF with a marked overlap

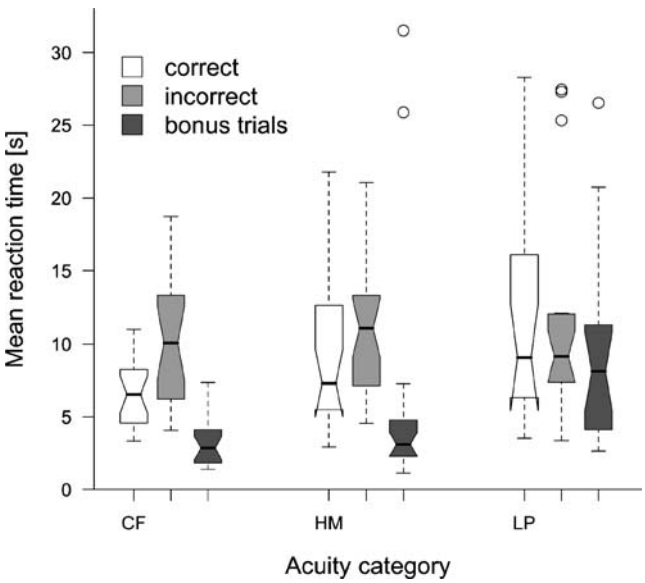

Fig. 3 Mean reaction times on presentation of a Landolt-C per acuity category and trial type across all runs. *White columns* represent average reaction times of trials with correct responses, in *light gray* the incorrect responses, and in *black* the bonus trials. The better the vision, the shorter the reaction time. Incorrect responses took longer. Bonus trials are easy and thus rapidly responded to. There is no difference among the three trial types in the LP patients because they hardly perceived any of them

Reproducibility versus number of FrACT trials

Test-retest variability was quantified via the 95% confidence interval for the difference of test minus re-test. When this was calculated for intermediate trial lengths (12, 18, 24 and 30 trials, Fig. 4) we found, unsurprisingly, that variability decreases with the number of trials. An ANOVA showed a significant drop in FrACT variability the longer the trial ($p<0.05$).

Discussion

Typically, VA in low vision patients is semi-quantitatively classified [12, 13] into the categories CF, HM and LP. In this study, we found that FrACT allowed VA to be quantified more precisely, even in the low-vision regions CF and HM, though it fails for LP. Quantitative measurements have been reported with FrACT down to HM categories [17] in 20 patients yielding mean $VA_{decimal}$ = 0.014±0.003 for CF-patients and 0.005±0.002 for HM-patients. In this study with 41 more patients we observed: CF≙0.010 and HM≙0.0052, thus the two studies coincide within less than ±0.1 logMAR.

Reproducibility of test / retest in our study was quantified via the 95% confidence interval for the test-retest difference. Based on 30 trials, with a value of 0.31 logMAR for the HM patients and 0.21 logMAR for the CF patients, this value compares surprisingly well with the 95% confidence interval of ±0.1 logMAR found in highly trained normal subjects [2], and also complies with [16] who assessed the reproducibility of FrACT in diabetic patients and [7] who presented an ETDRS-inspired computerized test. Even though the values of the first and second tests showed good agreement (Fig. 2), the second test's VA values were higher than those in the first test. This difference is very small, and may have to do with a residual learning process in spite of the training runs. In contrast to the CF and HM groups, the LP group's VA was not assessable with FrACT using the current parameters. It is possible, though unlikely in our opinion, that larger monitors would yield better results.

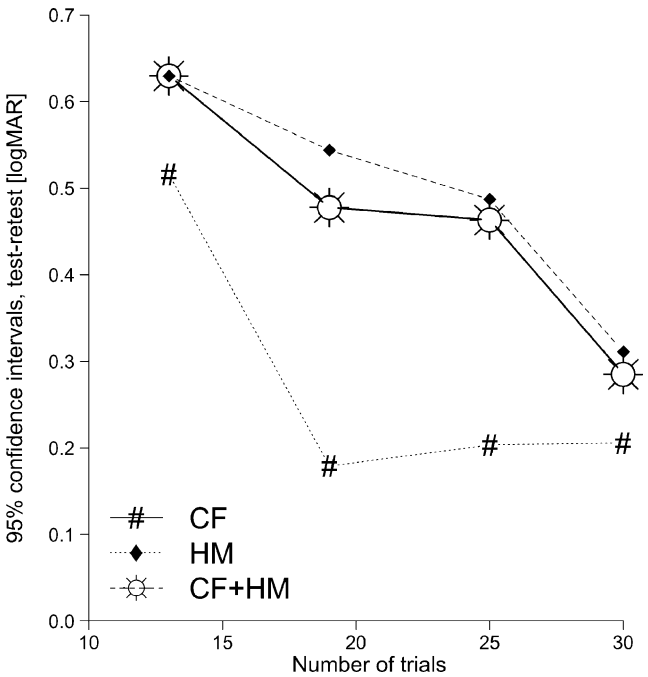

Fig. 4 Test-retest reproducibility after 12, 18, 24 and 30 trials (CF and HM patients only). Reproducibility is quantified as the 95% confidence interval of the test-retest differences. The confidence interval decreases markedly with the number of trials. Patients with CF have a better reproducibility than those with HM at all trial numbers

Interestingly, the CF and the HM group's visual acuities overlap considerably (see Fig. 2), while individual values are well reproduced by the second test. We interpret this as implying that the clinical allocation to the CF or HM group is only a rough classification, especially since a slight variation of our 30-cm testing distance may already lead to misclassifications. When using FrACT, the 50-cm testing distance can be accurately maintained by a cord attached to the chart, as previously described for other test charts in the low-vision field [8, 9]. Deviation of the testing-distance can thus be easily avoided.

When analyzing the overall duration of FrACT in different patient groups and recording the time needed for correct and incorrect responses, we obtained some interesting—albeit expected—results. The better the patient's VA, the less time he/she needs for correct trials or bonus trials. Also, the time required for eventually incorrect response is significantly longer than that for correct or bonus responses. The missing difference in LP patients—who need similar times for correct and incorrect responses—indicates that they merely guessed the gap's orientation for all Landolt rings. Repetition of the test decreases reaction times (possibly due to learning); while statistically significant, this effect size was small (around 10% faster for the second test).

There are practical considerations concerning the test's duration. When examining frail and older patients in particular, shortening the test time would be of considerable benefit—an advantage that comes at the expense of reliability, of course. Figure 4 shows that the test-retest 95% confidence interval declines up to the highest test length of 30 trials, as described previously [3, 6]. Less than 30 presentations, especially when using only four orientations with a corresponding guessing probability of 25%, seems too short, as desirable as it may be. We avoided trial lengths above 30 to avoid patient strain in this study, so we have no data concerning at what length any gain in

reproducibility would be offset by increased strain. Given these findings and those of [6, 16, 17, 19], we suggest testing with 30 optotypes when using four gap orientations. An alternative would be to test twice with a run length of 18, and to average the results. This would ensure high reliability while helping to assess reproducibility.

In summary, FrACT reproducibly measures VA down to the HM range, obtaining quantitative values. Based on the present results, CF and HM categories at 30 cm can be replaced by $VA_{decimal} = 0.01$ $(\triangleq VA_{logMAR} = 2.0)$ and 0.0052 $(\triangleq 2.3)$ respectively. Thus, three lines (in 0.1-log-unit steps) separate the HM and CF, which corroborates the clinical impression that the change in acuity from HM to CF is relevant. The acuity of LP patients could not be assessed with FrACT in its current incarnation.

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