



Reliability in perimetric multichannel contrast sensitivity measurements

Journal:	<i>Clinical and Experimental Optometry</i>
Manuscript ID:	CEOptom-13-282-OP.R1
Manuscript Type:	Original Research Paper
Date Submitted by the Author:	n/a
Complete List of Authors:	de Fez, Dolores; Universidad de Alicante, D. Óptica, Farmacología y Anatomía Capilla, Pascual; Universidad de Valencia, D. Optica Camps, Vicente; Universidad de Alicante, D. Óptica, Farmacología y Anatomía Luque, Maria José; Universidad de Valencia, D. Optica Moncho, Vicenta; Universidad de Alicante, D. Óptica, Farmacología y Anatomía
Keywords:	repeatability, reproducibility, contrast sensitivity, multichannel perimetry



1
2
3
4
5
6 **Title:** Reliability in perimetric multichannel contrast sensitivity measurements
7

8 **Running title:** Reliability in perimetric multichannel
9

10
11
12 **Authors**

13
14
15 Dolores de Fez (PhD),
16

17 Pascual Capilla⁺ (PhD),
18

19 Vicente Camps (PhD),
20

21 M^a José Luque⁺ (PhD),
22

23 Vicenta Moncho (DOO)
24
25
26
27

28 Dpto. Óptica, Farmacología y Anatomía, Universidad de Alicante
29

30 ⁺ Dpto. Óptica, Universidad de Valencia
31
32
33
34

35 **Corresponding Author**

36 Dolores de Fez
37

38 Dpto. Óptica, Farmacología y Anatomía, Universidad de Alicante,
39

40 Carretera San Vicente del Raspeig s/n - 03690 San Vicente del Raspeig –
41
42

43 Alicante
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4 Background: In this study, the reliability of perimetric contrast sensitivity
5 measurements favouring the achromatic, the red-green and the blue-yellow
6
7
8
9 postreceptoral mechanisms was analysed.

10
11 Methods: A new technique, multichannel ATD perimetry, provides spatial
12 and temporal stimuli favouring the detection by an achromatic mechanism (A),
13
14 from a magno or parvocellular origin, or by a red-green (RG) chromatic
15
16 mechanism, with a parvocellular origin, or a blue-yellow (BY) mechanism, with a
17
18 koniocellular origin. The repeatability and reproducibility of contrast sensitivity
19
20 measurements with these stimuli were studied in a group of 40 healthy subjects.
21
22 The analysis was carried out on 21 testing points within a 60°x40° fovea-
23
24 centered region of the visual field.
25
26
27

28
29 Results: The within-observer repeatability for the four mechanisms
30
31 studied is either good or excellent when the Intra-Class Correlation Coefficient
32
33 (ICC) can be calculated. For the remaining points, the Friedman's test finds that
34
35 the measurements are repeatable. The between-observer reproducibility was
36
37 either excellent or good in cases where the ICC applied and according to the
38
39 Friedman's test all results were reproducible.
40
41

42
43 Conclusions: The results obtained showed good repeatability and
44
45 reproducibility with achromatic, red-green and blue-yellow stimuli, although with
46
47 BY stimuli repeatability is slightly worse. Future studies on the diagnostic
48
49 validity of this device, are based on the fact that changes of sensitivity can be
50
51 compared by means of a visual single task, contrast sensitivity measurement,
52
53 and using a common metric.
54
55
56
57
58
59
60

1
2
3
4 **KEYWORDS:** multichannel perimetry, repeatability, reproducibility, agreement,
5
6 contrast sensitivity
7
8
9

10
11 The diagnosis of alterations of the visual system at an early stage is one
12 of the main objectives pursued by vision researchers. Early detection could stop
13 the loss of visual capabilities– even if not at present, maybe in the future, as
14 increasingly effective treatments are being developed- or at least minimize the
15 negative effects that some treatments produce.
16
17
18
19
20

21
22 It has been shown that diseases affecting visual function can damage the
23 mechanisms involved in spatial, chromatic and motion processing¹, causing
24 losses in contrast sensitivity both with stationary² and moving³ stimuli,
25 increasing thresholds in dark adaptation⁴ and provoking either generalized
26 colour contrast sensitivity losses or specific losses along the blue-yellow or de
27 red-green axes. Furthermore, congenital and acquired defects, caused by
28 diseases, medications or unhealthy habits, influence colour perception and
29 contrast sensitivity. For instance, losses in the chromatic or achromatic
30 mechanisms, or in both, have been reported in glaucoma^{1,5-8}, ocular
31 hypertension⁹, optical neuritis¹⁰, AMD (Age-related Macular Degeneration)¹¹,
32 diabetes^{2-4,12,13}, multiple sclerosis¹⁰, or Parkinson's disease¹⁴.
33
34
35
36
37
38
39
40
41
42
43
44
45

46 The perimetry tests more frequently used to diagnose and evaluate
47 losses of visual function are SAP perimetry (measurement of luminance
48 thresholds with white-on-white stimuli), SWAP (measurement of the luminance
49 thresholds to detect a blue stimulus against a yellow background) and FDT
50 (contrast thresholds with spatio-temporal achromatic stimuli). Both SWAP¹³, and
51
52
53
54
55
56
57
58
59
60

1
2
3
4 FDT¹⁵ perimetry seem capable of detecting functional damage in different
5
6 regions of the visual field before other characteristic symptoms of certain
7
8 diseases appear. For example, detection of damage in 10 to 30% of
9
10 hypertensive subjects¹⁶ and in 33.3% of subjects with suspected optic nerve
11
12 damage with SWAP has been reported¹⁷. A more specific test for the
13
14 parvocellular pathway, the high-resolution perimetry (HPRP), detects damage in
15
16 15 to 24% of hypertensive subjects¹⁶. Nowadays, to assess different visual
17
18 mechanisms of a patient, it is necessary to use a combination of devices. For
19
20 example, FTD perimetry to analyze the magnocellular pathway^{18,19}, HPRP to
21
22 analyze the parvocellular pathway^{20,21} or SWAP perimetry for the koniocellular
23
24 pathway^{22,23}. This identification of visual tasks with particular cellular pathways
25
26 is perhaps too simplistic (we refer the interested reader to Kaplan²⁴) and it is not
27
28 always clear how well a given technique isolates the responses of a particular
29
30 mechanism. See, for instance, White et al.²⁵ for a discussion about the relative
31
32 contributions of the magno and parvo pathways in the detection of FDT stimuli.
33
34 In the case of the blue-yellow mechanisms, although other cells with S-cone
35
36 input might mediate an S-off pathway^{26,27}, they represent a very small
37
38 percentage of the total population of cells with S-cone input²⁸, and their role in
39
40 detection tasks and in colour appearance is not clear at present. But admitting
41
42 that these different techniques do indeed favour different mechanisms, we find
43
44 that neither the tasks carried out by the patient nor the metrics used to express
45
46 the results are comparable, making the analysis of the relative losses incurred
47
48 by each mechanism difficult. In addition, commercial devices limit the capability
49
50 of the user to configure the spatial-temporal and chromatic characteristics of the
51
52
53
54
55
56
57
58
59
60

1
2
3
4 stimuli to adapt the design to particular aims of study –although recent efforts
5
6 have been made to overcome this limitation²⁹. For these two reasons, it would
7
8 be desirable to have a device with stimuli that could be configured to focus on
9
10 different visual pathways. In order to improve the performance of existing
11
12 diagnostic technologies, the Vision Group of the University of Valencia has
13
14 developed a new multichannel contrast sensitivity perimetry technique named
15
16 “ATD Multichannel Functional Test”³⁰. A, T and D stand in different colour vision
17
18 models for the three post-receptoral mechanisms, “achromatic” (A), “red-green”
19
20 (because this is the colour mechanism left to Tritanopes, hence the T) and
21
22 “blue-yellow” (because this is the colour mechanism left to Deuteranopes,
23
24 hence the D). Since this notation is not usual in clinical research, we will use in
25
26 what follows RG and BY instead when referring to the chromatic mechanisms.
27
28 The examiner may define stimuli in the desired directions in colour space^{31,32}
29
30 and choose the spatial and temporal frequency of the stimulus to favour a
31
32 particular mechanism (for example, magno or parvo when using achromatic
33
34 stimuli) while ensuring that the same task is performed by the patient for each
35
36 stimulus modality (see Appendix). This feature is essential in the process of
37
38 searching for the optimal stimulus to detect and evaluate damage caused by a
39
40 given pathology. For instance, in a recent study we have shown that chromatic
41
42 red-green and blue-yellow patterns with low spatial (0.5 cpd) and temporal (2
43
44 Hz) frequencies could be more sensitive for early detection of glaucomatous
45
46 damage than achromatic patterns, including low spatial-high temporal frequency
47
48 doubling stimuli (FDT perimetry)^{33,34}.
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4 The aim of our study is to demonstrate the reliability of the
5
6 psychophysical procedure used, assessing the repeatability and reproducibility
7
8 of the measurements made with our technique/device. The precision of a device
9
10 or clinical method is a factor that should be considered when conducting
11
12 method comparison studies. If a device has poor precision it is unlikely to have
13
14 good agreement with another device. Hence, comparing the precision of the two
15
16 devices or methods will provide greater insight into the source of eventual
17
18 differences. Repeatability and reproducibility are the two sides of precision³⁵.
19
20 Repeatability refers to the variability in repeated measurements by one subject
21
22 when all other factors are assumed constant (within-observer variability).
23
24 Reproducibility refers to the variability in repeated measurements when one or
25
26 more factors, such as observer, instrument, calibration or time is varied
27
28 (between-observer variability). In this paper, the changing factor is the clinician
29
30 conducting the test.
31
32
33
34
35
36

37 METHODOLOGY

39 **1. Device**

41
42 The ATD multichannel perimetry provides spatial and temporal stimuli for
43
44 determining contrast sensitivity measurements at different testing points in the
45
46 visual field, using a staircase psychophysical method. To evaluate the
47
48 achromatic mechanism A, a stimulus favouring the magnocellular pathway (A-
49
50 0.5cpd/12Hz) and other stimulus stimulating the parvocellular pathway (A-
51
52 4cpd/2Hz) were chosen. A large corpus of literature shows that the appearance
53
54 of spatio-temporal patterns at detection threshold depends on the ratio between
55
56
57
58
59
60

1
2
3
4 temporal and spatial frequency. Though frontiers are not sharply defined,
5
6 observers perceive either the temporal or the spatial pattern of the stimulus at
7
8 threshold, depending on whether the frequency ratio is either above 1-2
9
10 degrees/second or below this value³⁶⁻⁴⁰. According to the prevalent theory
11
12 linking visual functions and visual pathways (see again Kaplan²⁸), this result
13
14 would imply that detections would be mediated either by the magno or by the
15
16 parvo pathway, respectively. Our choice of stimuli is also supported by
17
18 experiments on selective lesions, which show that damage in the parvo
19
20 pathway greatly impairs the detectability of gratings in all the spatio-temporal
21
22 domain, except for the high temporal-low spatial frequency corner, and the
23
24 contrary happens when damage is confined to the magnocellular pathway⁴¹⁻⁴³.
25
26 It is not possible, however, to ensure that the parvo pathway does not contribute
27
28 to the detection of the A-0.5cpd/12Hz stimuli (see Anton et al.³⁴ for a
29
30 discussion). The red-green and blue-yellow chromatic mechanisms, putatively
31
32 mediated by the parvo and koniocellular pathways, respectively, were evaluated
33
34 by stimuli modulated along the RG and BY directions of color space, with a
35
36 spatial frequency of 0.5cpd and a temporal frequency of 2Hz (RG-0.5cpd/2Hz
37
38 and BY-0.5cpd/2Hz). The choice of these stimuli fulfilled two conditions: first,
39
40 the dynamic range of the device still allowed the measurement of the subject's
41
42 threshold⁴⁴ and second, the differences between normal and glaucomatous
43
44 patients were the largest we had obtained with our device³⁴. For a more detailed
45
46 explanation of the stimuli used, see the Appendix and Anton et al.³⁴.
47
48
49
50
51
52
53
54

55 ***Measurement procedure***

56
57
58
59
60

1
2
3
4 Measurements were carried out in a darkened room. During a session,
5
6 contrast sensitivity was measured at the 21 testing points described in the
7
8 Appendix. The screen is placed at 25 cm from the patients and therefore a 4.00
9
10 D lens was added to their refraction to avoid accommodation. After an
11
12 adaptation period of 30 seconds, the fixation stimulus flickered to signal the
13
14 beginning of the test and the first trial was presented. The subject was
15
16 instructed to press a button if any variation from the background was detected
17
18 at any point of the visual field. Subjects' responses caused the stimulus to
19
20 disappear from the display but counted as detections only if they occurred 100
21
22 ms after stimulus onset and before stimulus offset. The maximum duration of
23
24 the stimulus was 1 second. The time interval between trials was randomized by
25
26 the program, from 200 to 500 ms, to minimize the likelihood that subjects would
27
28 engage in rhythmic responses.
29
30
31

32
33 Thresholds were determined by an interleaved stepwise threshold
34
35 algorithm. At each trial, the testing point was changed at random. In the first trial
36
37 at a given testing point, the stimulus had the maximum amplitude achievable by
38
39 the CRT. If this stimulus was detected, amplitude was divided by 2 at the next
40
41 trial at that point, and continued decreasing in this way until the subject failed to
42
43 detect the stimulus. The staircase was then reversed and amplitude increased
44
45 by a $\sqrt{2}$ factor for the next presentation and continued increasing in this way
46
47 until the test was again detected. This triggered a second reversal, and
48
49 amplitude was divided by $\sqrt{2}$, and so on. Thus, the amplitudes (see Appendix)
50
51 at two consecutive trials at the same region, ΔR_{k-1} and ΔR_k , relate to each other
52
53 as follows (Equation 1):
54
55
56
57
58
59
60

$$\log_2(\Delta R_k) = \log_2(\Delta R_{k-1}) + \frac{(-1)^{n+1}}{2^n} \quad (1)$$

where n is the number of reversals until trial k . The criteria for exiting the staircase procedure at a given point were either totaling four reversals or 20 presentations, whatever came first. The staircase was also interrupted at a given point if a series of 5 consecutive stimuli with maximum amplitude passed undetected. Once a staircase was finished, threshold at that point, ΔR_{thres} , was defined as the amplitude value of the last detected stimulus. If no stimulus was detected, threshold was defined as the maximum amplitude value achievable by the device in the corresponding cardinal direction. Contrast sensitivity in decibels (dB) was computed as (Equation 2):

$$S = 10 \log_{10} \frac{\Delta R_{max}}{\Delta R_{thres}} \quad (2)$$

where ΔR_{max} is the maximum generable amplitude along the direction of the stimulus.

Control stimuli

Among the stimuli presentations, up to 16 false positive trials and 10 false negative trials were also randomly interleaved. Additionally, each session included up to 8 fixation-losses catch trials, presentations in the blind spot location previously estimated for the subject. These are $1.5^\circ \times 1.5^\circ$ squares with the same chromatic and spatial modulation as the false negative trials

1
2
3
4 (achromatic with $f_x=2$ cpd, without flicker), with maximum amplitude. Test results
5
6 were rejected if either the false positive or the false negative rate was over 33%,
7
8 or if fixation losses surpassed 20%.
9

10 11 12 13 **2. Selection of subjects**

14
15 We worked with a group of 40 healthy subjects aged between 20-35 and
16
17 measures were taken in one eye randomly chosen. The ocular and medical
18
19 history of the participants was examined, to discard those subjects with
20
21 symptoms or familiar antecedents of visual or systemic diseases affecting
22
23 vision. Preliminary tests included refraction, assessment of the anterior ocular
24
25 segment with a Topcon SL8Z Biomicroscope and of the posterior segment with
26
27 a Topcon TRC-NW6S Non-Mydriatic Retinal Camera, non-contact tonometry
28
29 with AT900®-Haag-Streit and the Farnsworth-Munsell 100-Hue colour-test.
30
31 Inclusion criteria were absence of ocular and systemic diseases that could
32
33 affect vision, intra-ocular pressure (IOP) values below 21 mm Hg, spherical
34
35 equivalent below 4D and cylinder below 2D, 20/25 Snellen visual acuity or
36
37 better and normal chromatic discrimination as assessed by the Farnsworth-
38
39 Munsell100-Hue test. The study adheres to the tenets of the Declaration of
40
41 Helsinki for Research Involving Human Observers.
42
43
44
45
46
47

48 49 **3. Experimental design and development of the measurement** 50 51 **sessions**

52
53 The 40 subjects were divided into two groups of 20 subjects each. Group
54
55 1 underwent testing with stimulus A-0.5cpd/12Hz and A-4cpd/2Hz, to evaluate,
56
57
58
59
60

1
2
3
4 respectively, the achromatic mechanisms of magnocellular and parvocellular
5
6 origin (in what follows, A-Magno and A-Parvo for short). Group 2 underwent
7
8 testing for the red-green (RG-0.5cpd/2Hz) and blue-yellow (BY-0.5cpd/2Hz)
9
10 chromatic mechanisms (in what follows RG and BY for short).

11
12 Each subject underwent four perimetry tests with each of the two
13
14 stimuli assigned to their group: three perimetry tests were conducted by
15
16 Clinician 1 and one by Clinician 2. Data measured by Clinician 1 was used in
17
18 the repeatability study, the comparison between Clinicians 1 and 2 constituted
19
20 the reproducibility study. Tests took place on different days to avoid the
21
22 influence of fatigue. In the first day, the preliminary tests to determine whether
23
24 the subject met the inclusion criteria were carried out and the subject performed
25
26 the four perimetry tests for each of the two stimuli assigned to his/her group in
27
28 two different days. The first two tests were conducted by Clinician 1, in the two
29
30 last ones Clinicians 1 and 2 alternated in random order. In this way, we
31
32 expected to reduce possible learning effects in the reliability study.
33
34
35
36

37 Each perimetry test took about 4 to 8 minutes, depending on the
38
39 subject and on the stimulus characteristics (A-Magno: 7.7 ± 0.7 min, A-Parvo:
40
41 4.1 ± 0.6 min, RG: 4.9 ± 0.4 min, BY: 5.7 ± 0.4 min). The subject rested for 10
42
43 minutes between perimetry tests and the duration of a complete measurement
44
45 session was always kept below one hour.
46
47
48
49

50 51 **4. Statistical analysis**

52
53 The statistical tests were performed using SPSS v. 14.0.1 for Windows
54
55 (SPSS Inc., Chicago, IL, USA). Besides analyzing the results obtained at the
56
57
58
59
60

1
2
3
4 different testing points, we have considered groupings in three zones: the fovea
5
6 (point 11, see Table 1), the perifovea, which comprises the four points
7
8 surrounding the fovea (points 8, 9, 13 and 14) and the extrafovea (remaining
9
10 points).

11
12
13 The study of the reliability of our device follows the guidelines laid out by
14
15 the International Organization for Standardization (IOS) and we have adopted
16
17 their definitions of repeatability and reproducibility³⁵. In the literature on
18
19 automated perimetry reliability with normal subjects, a great variety of
20
21 methodologies is used, but the IOS guidelines are not followed⁴⁵⁻⁴⁷. The
22
23 normality of the samples was evaluated using the Shapiro-Wilk test at the 95%
24
25 significance level, as recommended for samples with less than 30 subjects, and
26
27 the appropriate parametric or non-parametric tests applied in consequence⁴⁸⁻⁵⁰.

28
29 For normally distributed data, the concordance-coincidence between
30
31 multiple measures of the same variable was assessed with the Intraclass
32
33 Correlation Coefficient (ICC)⁵¹, both in the study of within-observer concordance
34
35 (repeatability) and in the study of between-observer concordance
36
37 (reproducibility). According to the value of this coefficient, measurement
38
39 reliability is labelled as: absent (0), low (<0.4), between regular and good ([0.4-
40
41 0.75]) and excellent (> 0.75)⁵¹.

42
43
44
45
46 Friedman's nonparametric test of k-related samples was carried out if the
47
48 distributions were not normal. An asymptotic significance greater than 0.05 with
49
50 this test indicates that there are not significant differences between the
51
52 measurements, that are therefore considered repeatable or reproducible^{48,49,52}.

RESULTS

Mean sensitivity values for each stimulus are summarized at Tables 1 and 2. It can be seen that the A-Magno mechanism has the highest values of sensitivity for all points, followed by the BY mechanism. On the contrary, the A-Parvo mechanism has very low values of sensitivity, except in the fovea and the perifovea. The RG mechanism shows the highest sensitivity averages in the fovea and perifovea and some points of the extrafovea (4, 5, 17, 18), but the values are always lower than those of the A-Magno mechanism. Sensitivity determines the mean number of trials (MNT) needed to measure threshold, therefore MNT decreases with eccentricity and is in general greater for the A-Magno and BY stimuli than for RG and A-Parvo. The limit of 20 presentations is only occasionally reached with certain subjects at random locations with the A-Magno stimulus, hardly 5% of the total number of measurements.

From the measures of sensitivity in the four mechanisms (A-Magno, A-Parvo, RG and BY) the repeatability of the instrument and the concordance between results from the two clinicians were analysed.

1. Within-observer Repeatability

The results of the repeatability analysis for our four stimuli are summarized in Table 1. There appears the mean and the standard deviation of the sensitivity, and either the ICC values or the p-value of Friedman's test, as appropriate. Figure 1 presents the point-by-point repeatability classification for

1
2
3
4 each of the four mechanisms. In this figure, the visual field has been divided in
5
6 $10^{\circ} \times 10^{\circ}$ regions, centered in each of the testing points.
7

8
9 **Insert Figure 1 here**

10
11 In the A-Parvo mechanism, sensitivity data at most points at the
12
13 extrafovea (76%) present non-normal distributions. All these measurements are
14
15 repeatable according to the Friedman's test. Fovea and perifovea present
16
17 normal distributions and the repeatability is excellent in all cases (see ICC
18
19 value). In the A-Magno mechanism, most of the points present normal
20
21 distributions with repeatability between excellent (67%) and good (19%). At the
22
23 perifovea, which does not follow the normal distribution (14%), within-observer
24
25 measurements are repeatable. In the RG mechanism, most points present a
26
27 normal distribution and the repeatability is excellent (62%), with a reduced
28
29 number that are rated as just good (14%). In all cases where the distribution is
30
31 not normal (24%), the Friedman's test proves that the measures are repeatable.
32
33 In the BY mechanism most data distributions are normal, and the ICC values
34
35 show that repeatability is excellent (38%) or good (48%). For points with non-
36
37 normally distributed data (14%), the results are repeatable in all cases.
38
39

40
41
42 In summary, within-observer repeatability for the four mechanisms
43
44 studied is either good or excellent when the ICC can be calculated. For the rest
45
46 of points, the Friedman's test finds that the measurements are repeatable.
47
48

49
50
51 **2. Between-observer Reproducibility**

52
53 To check the reproducibility, we compared two measurements
54
55 supervised by different clinicians. The third perimetry test of Clinician 1 was
56
57
58
59
60

1
2
3
4 compared with the single measurement performed by Clinician 2. As in the
5
6 previous study, the normality of the sensitivity distributions was analysed and
7
8 the appropriate reliability test for each case was applied. The results are shown
9
10 in Table 2, using the same criteria as in Table 1. In Figure 2 presents the point-
11
12 by-point reproducibility classification of for each of the four mechanisms.
13
14

15 **Insert Figure 2 here**

16
17 In the A-Parvo mechanism, most points in the extrafovea follow non-
18
19 normal distributions, and all points have proved to be reproducible according to
20
21 the Friedman's test. As in the previous section, the distributions are normal in
22
23 fovea and perifovea and reproducibility is excellent at all testing points. In most
24
25 testing points, data from the A-Magno mechanism follow normal distributions
26
27 with reproducibility between excellent (48%) and good (19%). In comparison
28
29 with the data presented in the within-observer study, a larger number of
30
31 extrafoveal points but just one at perifovea (up to a total of 33%) do not follow
32
33 the normal distribution. Friedman's analysis indicates that all the measurements
34
35 are reproducible. With the RG stimulus, most points follow the normal
36
37 distribution and reproducibility results are either excellent (52%) or good (24%).
38
39 In all cases where the distribution is not normal (24%), the Friedman's test
40
41 indicates that the measurements are reproducible. With regard to the BY
42
43 stimulus, most of the data distributions are normal, and the ICC test results are
44
45 either excellent (38%) or good (48%). In the regions with non-normal
46
47 distributions (24%), the result is always reproducible.
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4 In summary, the between-observer reproducibility was either excellent
5
6 or good in cases where the ICC applied and according to the Friedman test all
7
8 results were reproducible.
9

10 11 12 **DISCUSSION**

13
14
15 A study of the reliability of the multichannel perimeter has been designed
16
17 for the A-Magno, A-Parvo, RG and BY mechanisms. A sample of 40 normal
18
19 subjects divided in two groups have participated in this study. All the subjects
20
21 carried out four repeated perimetry tests, three under the supervision of a
22
23 clinician (within-observer study) and one under the supervision of a different
24
25 clinician (between-observer study). We have found that the within-observer
26
27 measures are repeatable, i.e. there is no significant variability in the repetition of
28
29 the measurements of an subject when other factors remain constant. In the
30
31 between-observer study we have concluded that the measurements conducted
32
33 by both clinicians are interchangeable.
34
35
36

37
38 In general, almost all measurements follow a normal distribution of the
39
40 responses for all mechanisms. The points where sensitivity data are not
41
42 normally distributed do not seem to follow a systematic pattern, common to all
43
44 the stimuli, such as a dependence on eccentricity. The sole exception is the A-
45
46 Parvo stimulus, which does not follow the normal distribution in the majority of
47
48 the points, possible due to the subjects's low sensitivity outside the perifovea.
49
50 However, in the fovea and the perifovea the distribution of responses follows the
51
52 normal distribution.
53
54
55
56
57
58
59
60

1
2
3
4 It is difficult to compare our reliability study with the literature, due to
5
6 differences in the reliability criteria and in the number of measurements, in the
7
8 structure of a measurement session and in the factors that change between
9
10 measurements⁴⁵⁻⁴⁷. In spite of this, we may conclude that our multichannel
11
12 perimeter presents standard deviation values similar to other studies with
13
14 different devices and furthermore, our precision (ICC) results are as good as
15
16 those obtained in other types of perimeter^{46,47}.
17
18

19
20 The reasons for this good performance may lie in the psychophysical
21
22 measurement procedure used and in the comparatively reduced number of
23
24 points tested in the visual field. It has been shown that measurement
25
26 repeatability depends on a large number of factors: number of testing points in
27
28 the visual field and number of stimulus presentations in the measurement
29
30 procedure^{45,47,53,54}, the spatio-temporal characteristics of the stimulus^{45,53,54}, the
31
32 patient's sensitivity (determined either by eccentricity⁵³, age^{47,53} or by damage in
33
34 the visual system⁴⁶), previous experience^{53,55}, and so on... The four tests we
35
36 have analysed have in common the distribution of testing points, the task to be
37
38 performed by the observer and the psychophysical method, and therefore
39
40 potential differences in repeatability must arise from the stimulus characteristics
41
42 –which determine sensitivity, for instance, and therefore the number of trials
43
44 needed to determine threshold, another relevant factor- or from the different
45
46 limitations that the dynamic range of the device sets in each direction of colour
47
48 space. The analysis of our results becomes complicated by the fact that there is
49
50 not a common metric for repeatability for all testing points, and whereas ICC
51
52 grades the results, the Friedman test doesn't. Considering only those testing
53
54
55
56
57
58
59
60

1
2
3
4 points where the ICC could be computed, we used a general linear model to
5
6 determine which variables determined repeatability and reproducibility. ICC
7
8 was the dependent variable, mean sensitivity of the population sample,
9
10 eccentricity, and mean number of trials needed to determine threshold –which
11
12 changed with location in the visual field and stimulus type- were the
13
14 independent variables and stimulus type was a factor. The analysis showed that
15
16 the only significant difference was with stimulus type ($\sigma < 0.001$) and that
17
18 repeatability results were significantly worse for the blue-yellow stimulus.
19
20 Comparisons between SAP and SWAP perimetry also show that repeatability
21
22 with blue-yellow stimuli is worse⁵³. In the between-observer study, ICC did not
23
24 significantly depend on any of the variables listed above.
25
26
27

28
29 We have shown, therefore, that the accuracy of the device, in general, is
30
31 good, although it must still be shown that the same good results hold with an
32
33 older population sample. The study with older adults is necessary and is at
34
35 present a work on progress. Data from glaucoma and OHT subjects that we
36
37 have previously published³³ suggest that the A-4cpd/2Hz stimulus is likely to be
38
39 the least useful of the four we have studied in this paper. The potential great
40
41 advantage of this device is the versatility in designing visual stimulus, which
42
43 allows a variety of studies based on the cells/mechanisms involved in the
44
45 detection, which could help to find optimal stimuli for detecting and monitoring
46
47 visual damage. For instance, it has been recently shown that chromatic red-
48
49 green and blue-yellow patterns with low spatial (0.5 cpd) and temporal (2 Hz)
50
51 frequencies could be more sensitive for early detection of a glaucomatous
52
53 damage than achromatic patterns, including low spatial-high temporal frequency
54
55
56
57
58
59
60

1
2
3
4 doubling stimuli (FDT perimetry)³⁴. Moreover, these stimuli detected damage in
5
6 ocular hypertensive and glaucoma suspect patients^{33,34}. These results are
7
8 promising for future use of the device for the early detection of pathologies that
9
10 affect the visual system, when the relevant normative database of the normal
11
12 population has been completed.
13
14

15
16
17 **Disclosure of potential conflict of interest:** Dolores de Fez, Vicente Camps
18
19 and Vicenta Moncho have no proprietary interest in any material or instrument
20
21 used in this study. P Capilla and MJ Luque, have an intellectual proprietary
22
23 interest in the ATD multichannel perimeter patent (US 7.641.344 B2).
24
25
26

27
28 **Acknowledgements.** The ATD multichannel perimeter was built thanks to the
29
30 support of the Spanish Ministerio de Ciencia y Tecnología Grants DPI2000-0116-
31
32 P4-02 and PTR 1995-0909-OP, in collaboration with INDUSTRIAS DE OPTICA
33
34 SA (San Cugat del Vallés, Spain).
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Table 1: Results from the within-observer study. Mean sensitivities (dB) obtained in three measurements with Clinician 1, with their standard deviation (SD) and the results of the repeatability test (Friedman's p-value or ICC) in each mechanism, at each of the 21 testing points in the visual field. (x,y) are the spatial coordinates of each point, in degrees, referred to a coordinate system with origin in fovea.

Point	(x,y)	A-Parvo			A-Magno			RG			BY		
		mean \pm SD (dB)	FRIEDMAN	ICC	mean \pm SD (dB)	FRIEDMAN	ICC	mean \pm SD (dB)	FRIEDMAN	ICC	mean \pm SD (dB)	FRIEDMAN	ICC
1	(-25,5)	0.04 \pm 0.22	0.36		11.3 \pm 3.1		0.91	0.3 \pm 0.5	0.85		4 \pm 2.1		0.84
2	(-25,-5)	0.15 \pm 0.54	0.06		11.2 \pm 3.4		0.94	0.4 \pm 1	0.83		4.2 \pm 1.9		0.86
3	(-15,15)	0.1 \pm 0.3	0.06		13.1 \pm 1.8		0.83	0.4 \pm 0.7	0.35		5.6 \pm 1.8		0.79
4	(-15,5)	1.3 \pm 1.4	0.51		14.2 \pm 1.4		0.9	4.6 \pm 1.4		0.86	8.3 \pm 1.2		0.63
5	(-15,-5)	1.2 \pm 1.5	0.1		15.3 \pm 1.6		0.62	4.8 \pm 1.3		0.9	8.4 \pm 1.8		0.71
6	(-15,-15)	0.2 \pm 0.7	0.9		12.6 \pm 3.3		0.93	1 \pm 1		0.9	6 \pm 1.6		0.7
7	(-5,15)	1.8 \pm 2.3	0.62		14.1 \pm 1.8		0.77	2.2 \pm 1.3		0.88	7 \pm 1.8		0.48
8	(-5,5)	5.3 \pm 3.6		0.95	16.4 \pm 2.4	0.25		8 \pm 1.6		0.8	8.7 \pm 1.8	0.08	
9	(-5,-5)	4.6 \pm 3.3		0.92	16.3 \pm 2	0.41		7.9 \pm 1.4		0.8	8.8 \pm 1.7		0.6
10	(-5,-15)	1.3 \pm 1.5	0.6		14 \pm 2.7		0.92	3.5 \pm 1.2		0.85	7.2 \pm 1.8		0.56
11	(0,0)	8.3 \pm 3.5		0,9	18 \pm 2.4		0.55	10.8 \pm 2.2		0.71	9.6 \pm 1.7		0.76
12	(5,15)	1.2 \pm 1.9	0.07		13.4 \pm 2		0.77	1.9 \pm 1.4		0.84	5.9 \pm 1.9		0.68
13	(5,5)	5.2 \pm 3		0,89	16.8 \pm 2.1	0.35		8.3 \pm 1.7		0.54	9 \pm 1.6		0.65
14	(5,-5)	5.3 \pm 3.1		0,81	16.9 \pm 1.2		0.69	8.3 \pm 1.5		0.64	9.1 \pm 1.8	0.82	
15	(5,-15)	1.7 \pm 2.4	0.06		14.4 \pm 3.2		0.92	4.4 \pm 1.5	0.54		7.6 \pm 1.4	0.07	
16	(15,15)	0.1 \pm 0.5	0.46		13.6 \pm 1.3		0.87	0.7 \pm 0.8	0.21		5.4 \pm 1.6		0.8
17	(15,5)	1.1 \pm 1.6	0.25		14.6 \pm 1.4		0.81	4.2 \pm 1.5		0.82	6.7 \pm 1.7		0.72
18	(15,-5)	1.4 \pm 2	0.26		14.9 \pm 2.1		0.59	4.8 \pm 1.4		0.81	7.3 \pm 1.9		0.71
19	(15,-15)	0.5 \pm 1	0.26		13.8 \pm 3.5		0.97	2.7 \pm 1.3		0.84	6 \pm 2		0.79
20	(25,5)	0.2 \pm 0.4	0.05		13.2 \pm 3		0.88	1.8 \pm 1.4		0.83	5.2 \pm 2.6		0.84
21	(25,-5)	0.2 \pm 0.5	0.33		12.5 \pm 3.4		0.97	2 \pm 1.5		0.77	4.8 \pm 2.5		0.93

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49

Table 1: Results of the between-observer study. Mean sensitivities (dB) obtained in two measurements with two different clinicians, their standard deviation (SD) and the results of the reproducibility test (Friedman's p-value or ICC) in each mechanism, at each of the 21 testing points in the visual field. (x,y) are the spatial coordinates of each point, in degrees, referred to a coordinate system with origin in fovea.

Point	(x,y)	A-Parvo			A-Magno			RG			BY		
		mean ± SD (dB)	FRIEDMAN	ICC	mean ± SD (dB)	FRIEDMAN	ICC	mean ± SD (dB)	FRIEDMAN	ICC	mean ± SD (dB)	FRIEDMAN	ICC
1	(-25,5)	0.05 ± 0.2	0.32		11.3 ± 2.8	0.49		0.3 ± 0.5	0.41		3.8 ± 2.1	0.15	
2	(-25,-5)	0.2 ± 0.6	0.18		11 ± 3.3	0.25		0.4 ± 0.9	0.65		4.1 ± 1.8		0.75
3	(-15,15)	0.05 ± 0.2	0.56		13.2 ± 2	0.37		0.4 ± 0.7	1		5.6 ± 1.2		0.77
4	(-15,5)	1.2 ± 1.3	1		15.4 ± 1.5		0.75	4.7 ± 1.3		0.8	8.2 ± 1.1		0.78
5	(-15,-5)	1 ± 1.4	0.8		15.2 ± 1.7		0.6	4.9 ± 1.3		0.8	8.3 ± 1.4		0.54
6	(-15,-15)	0.2 ± 0.9	0.31		12.6 ± 3.4	0.46		1 ± 0.9	0.56		5.9 ± 1.7		0.51
7	(-5,15)	1.8 ± 2.1	1		14.4 ± 1.7		0.75	2.3 ± 1.4		0.8	7.1 ± 1.6		0.63
8	(-5,5)	5 ± 3.6		0.75	16.3 ± 2.8		0.77	8 ± 1.8		0.6	8.5 ± 2		0.66
9	(-5,-5)	4.2 ± 3.3		0.9	16.1 ± 2.3		0.8	7.9 ± 1.4		0.7	8.7 ± 1.7		0.7
10	(-5,-15)	1.1 ± 1.6	1		14.1 ± 3		0.78	3.4 ± 1.4		0.9	7.1 ± 1.8		0.68
11	(0,0)	8 ± 3.4		0.75	18 ± 2.7		0.85	10.6 ± 2.3		0.8	9.6 ± 1.7		0.85
12	(5,15)	1 ± 1.7	0.29		13.4 ± 2.3		0.5	2 ± 1.5		0.8	5.8 ± 1.9		0.7
13	(5,5)	4.9 ± 2.9		0.9	16.6 ± 2.3	0.25		8.3 ± 1.8		0.8	8.9 ± 1.7		0.6
14	(5,-5)	4.9 ± 3		0.75	16.8 ± 1.2		0.7	8.1 ± 1.6		0.6	9 ± 1.8		0.7
15	(5,-15)	1.4 ± 2	0.46		14.3 ± 3.3		0.77	4.5 ± 1.4		0.6	7.5 ± 1.5		0.71
16	(15,15)	0.1 ± 0.3	0.66		13.5 ± 1.3		0.78	0.7 ± 0.9	0.13		5.3 ± 1.4	0.63	
17	(15,5)	1 ± 1.5	0.56		14.4 ± 1.5		0.6	4.3 ± 1.5		0.9	6.3 ± 1.7		0.78
18	(15,-5)	1.4 ± 1.9	0.62		14.7 ± 2.5		0.85	4.8 ± 1.4		0.9	7.1 ± 2.1		0.8
19	(15,-15)	0.5 ± 1	0.32		13.8 ± 3.5	0.79		2.7 ± 1.4		0.9	6 ± 2	0.43	
20	(25,5)	0.1 ± 0.3	0.56		13 ± 3		0.81	2 ± 1.4		0.84	2.5 ± 2.5		0.95
21	(25,-5)	0.2 ± 0.4	0.41		12.4 ± 3.5	0.65		2.1 ± 1.6		0.6	4.5 ± 2.4		0.95

REFERENCES

1. Pacheco-Cutillas M, Sahraie A, Edgar D. Acquired colour vision defects in glaucoma- their detection and clinical significance. *British Journal of Ophthalmology*. 1999;83:1396-402.
2. Verroti A, Lobefalo L, Petitti M, Mastropasqua L, Morgese G, Chiarelli F, et al. Relationship between contrast sensitivity and metabolic control in diabetics with and without retinopathy. *Ann Med*. 1998;30:369-74.
3. Kawasaki K, Yonemura K, Yokogawa Y, Saito N, Kawakita S. Correlation between ERG oscillatory potential and psychophysical contrast sensitivity in diabetes. *Doc Ophtalmol*. 1986;64:209-15.
4. Greenstein V, Shapiro A, Hood D, Zaidi Q. Chromatic and luminance sensitivity in diabetes and glaucoma. *J Opt Soc Am* 1993;10:1785-91.
5. Leeprechanon N, Giangiacomo A, Fontana H, Hoffman D, Capriloli J. Frequency-Doubling Perimetry: Comparison with Standard Automated Perimetry to detect Glaucoma. *American Journal of Ophtalmology*. 2007;143:263-71.
6. Castelo-Branco M, Faria P, Forjaz V, Kozak LR, Azevedo H. Simultaneous comparison of relative damage to chromatic pathways in ocular hypertension and glaucoma: correlation with clinical measures. *Invest. Ophthalmol. Vis. Sci*. 2004;45:499-505.
7. McKendrick AM, Sampson GP, Walland MJ, Badcock DR. Contrast sensitivity changes due to glaucoma and normal aging: low-spatial-frequency

- 1
2
3
4 losses in both magnocellular and parvocellular pathways. *Invest. Ophthalmol.*
5
6 *Vis. Sci.* 2007;48:2115-2122.
7
8 8. Ferreras A, Polo V, Larrosa JM, et al. Can frequency-doubling technology
9
10 and short-wavelength automated perimetries detect visual field defects before
11
12 standard automated perimetry in patients with preperimetric glaucoma? *J*
13
14 *Glaucoma* 2007;16:372-83.
15
16 9. Johnson CA, Brandt JD, Khong AM, Adams AJ. Short-wavelength automated
17
18 perimetry in low-, medium-, and high-risk ocular hypertensive eyes. Initial
19
20 baseline results. *Arch Ophthalmol* 1995;113:70-6.
21
22 10. Porciatti V, Sartucci F. Retinal and cortical evoked responses to chromatic
23
24 contrast stimuli. Specific losses in both eyes of patients with multiple sclerosis
25
26 and unilateral optic neuritis. *Brain* 1996;119(Pt 3):723-40.
27
28 11. Phipps J, Dang T, Vingrys A, Guymer R. Flicker perimetry losses in Age-
29
30 related Macular Degeneration. *Invest. Ophthalmol. Vis. Sci.* 2004;45(9):3355-
31
32 60.
33
34 12. Nomura R, Terasaki H, Hirose H, Miyake Y. Blue-on-yellow perimetry to
35
36 evaluate S cone sensitivity in diabetics. *Ophthalmic Res.* 2000;32:69-72.
37
38 13. Afrashi F, Erakgun T, Kose S, et al. Blue-on-yellow perimetry versus
39
40 achromatic perimetry in type 1 diabetes without retinopathy. *Diabetes Res Clin*
41
42 *Pract* 2003;61:7-11.
43
44 14. Müller T, Voitalla D, Peters S, Kohla k, Przuntek H. Progress of visual
45
46 dysfunction in Parkinson's disease. *Acta Neural Scand.* 2002;105:256-60.
47
48 15. Realini T, Lai M, Barber, editors. Impact of diabetes on glaucoma screening
49
50 using frequency-doubling perimetry. Conference Information: Annual Meeting of
51
52
53
54
55
56
57
58
59
60

1
2
3
4 the Association-for-Research-in Vision-and-Ophtalmology, May 04-09; 2003; Ft
5
6 Lauderdale, Fl: Ophtalmology.

7
8
9 16. Johnson C, Brandt J, Khong A, Adams A. Short-wavelength automated
10
11 perimetry in low-, medium-, and high-risk ocular hypertensive eyes. Initial
12
13 baseline results. *Arc Ophthalmol.* 1995;113:70-6.

14
15 17. Ferreras A, Polo V, Larrosa J. Can frequency-doubling technology and
16
17 short-wavelength automated perimetries detect visual field defects before
18
19 standard automated perimetry in subjects with preperimetric glaucoma? *J*
20
21 *Glaucoma.* 2007;16:372-83.

22
23 18. Quigley H. Identification of glaucoma-related visual field abnormality with
24
25 screening protocol of frequency doubling technology. *Am J Ophthalmol.*
26
27 1998;125:819-29.

28
29 19. Johnson C, Cioffi G, Van Buskirk E. Frequency doubling technology
30
31 perimetry using a 24-2 stimulus presentation pattern. *Optom and Vis Sci.*
32
33 1999;76:571-81.

34
35 20. Wanger P, Oeresson H. Pattern-reversal electroretinograms and high-pass
36
37 resolution perimetry in suspected or early glaucoma. *Ophtalmology.*
38
39 1987;94:1098-103.

40
41 21. Chauhan B, LeBlanc R, McCornick T, Rogers J. Comparison high-pass
42
43 resolution perimetry and pattern discrimination perimetry to conventional
44
45 perimetry in glaucoma. *Can J Ophtalmol.* 1993;28:306-11.

46
47 22. Sample P, Johnson C, Haergerstrom-Portnoy G. Optimun parameters for
48
49 short-wavelength automated perimetry. *J Glaucoma.* 1996;5:375-83.
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4 23. Sample P, Boswoth C, Weinreb R. Short-wavelength automated perimetry
5 and motion automated perimetry in subjects with glaucoma. Arch Ophtalmol.
6 1997;115:1129-33.
7
8
9
10 24. Kaplan, E. (2008). The M, K, and P Streams in the Primate Visual System:
11 what do they do for vision? Chapter 1.16, pages 369–382. The Senses.
12 Elsevier, UK
13
14
15 25. White AJ, Sun H, Swanson WH, Lee BB. An examination of physiological
16 mechanisms underlying the frequency-doubling illusion. Invest Ophthalmol Vis
17 Sci. 2002;43:3590–3599.
18
19
20
21
22
23 26. Klug K, Herr S, Tratt Ngo I, Sterling P, Schen S. Macaque Retina Contains
24 and S-cone off midget pathway. J Neurosci. 2003;23:9881-9887.
25
26
27
28 27. Dacey DM, Liao HW, Peterson BB, Robinson FR, Smith VC Pokorny J,
29 King-Wai Y and Gamlin P. Melanopsin-expressing ganglion cells in primate
30 retina signal colour and irradiance and project to the LGN. Nature, 2005, 433:
31 749–754.
32
33
34
35
36 28. Valberg A, Lee BB, Tigwell DA. Neurons with strong inhibitory S-cone inputs
37 in the macaque lateral geniculate nucleus. Vision Res. 1986, 26:1061-1064.
38
39
40
41 29. Turpin A, Artes PH, McKendrick AM, The Open Perimetry Interface: an
42 enabling tool for clinical visual psychophysics, Journal of Vision, 2012, 12, 1-5.
43
44
45 30. ATD Double Modulation Analyzer, patent US 7.641.344 B2 and 2246174
46 ES.
47
48
49 31. Krauskopf J WD, Heeley DW. Cardinal directions of colour space. Vision
50 Res. 1982;22:1123-31.
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4 32. Derrington AM, Krauskopf J, Lennie P. Chromatic mechanisms in lateral
5 geniculate nucleus of macaque. *The Journal of Physiology*. 1984;357:241-65.
6
7 Epub 1984/12/01.
8
9
10 33. Morilla-Grasa A AA, Santamaría S, et al. Contrast sensitivity differences
11 between glaucoma, ocular hypertensive and glaucoma suspect subjects found
12 by ATD perimetry. *Invest Ophthalmol Vis Sci ARVO*. 2009;50(5):E-Abstract 5290.
13
14 34. Antón A, Capilla P, Morilla-Grasa A, Luque MJ, Artigas JM, FelipeA.
15 Multichannel Functional Testing in Normal Subjects, Glaucoma Suspects, and
16 Glaucoma Patients. *Invest. Ophthalmol. Vis. Sci*. December 2012 53:8386-
17 8395; published ahead of print October 11, 2012, doi:10.1167/iovs.12-9944.
18
19 35. ISO. Accuracy (Trueness and Precision) of Measurement Methods and
20 Results. Part1 and 2. Basic Methods for the Determination of Repeatability and
21 Reproducibility of a Standard Measurement Method. In: Standardization. IOF,
22 editor. Geneva, Switzerland: ISO, (ISO 5725-2); 1994.
23
24 36. Koenderink JJ, van Doorn AJ. Spatiotemporal contrast surface is bimodal.
25 *Opt Lett*. 1979;4:32-34.
26
27 37. Harris MG. Velocity specificity of the flicker to pattern sensitivity ratio in
28 human vision. *Vision Res*. 1980;20:687-691.
29
30 38. Burbeck CA. Criterion-free pattern and flicker thresholds. *J Opt Soc Am*.
31 1981;71:1343-1350.
32
33 39. Murray I, MacCana F, Kulikowski JJ (1983). Contribution of two movement
34 detecting mechanisms to central and peripheral vision. *Vision Res*. 1983;23:
35 151-159.
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4 40. Panish SC, Swift DJ, Smith RA (1983) Two-criterion threshold techniques:
5
6 evidence for separate spatial and temporal mechanisms? *Vision Res.* 1983;23:
7
8 1519-1525.
9
- 10 41. Merigan WH, Katz LM y Maunsell JHR. The effects of parvocellular lateral
11
12 geniculate lesions on the acuity and contrast sensitivity of macaque monkeys. *J.*
13
14 *Neurosci.* 1991;11:994-1001.
15
- 16 42. Merigan W.H., Byrne C y Maunsell J.H.R. Does primate motion perception
17
18 depend on the magnocellular pathway? *J. Neurosci.* 1991;11:3422-3429.
19
- 20 43. Merigan WH, Maunsell JHR. How parallel are the primate visual pathways?
21
22 *Ann Rev Neurosci.* 1993;16:568-78.
23
- 24 44. Díez-Ajenjo M, Capilla P, Luque M. Red-green vs. blue-yellow spatio-
25
26 temporal contrast sensitivity across the visual field. *J Modern Optics.*
27
28 2011;58:1736-1748.
29
- 30 45. Wall M, Woodward KR, Doyle CK, Artes PH. Repeatability of Automated
31
32 Perimetry: A Comparison between Standard Automated Perimetry with Stimulus
33
34 Size III and V, Matrix, and Motion Perimetry. *Invest. Ophthalmol. Vis. Sci.*
35
36 2009;50(2):974-9.
37
- 38 46. Kim LS, McAnany JJ, Alexander KR, Fishman GA. Intersession repeatability
39
40 of Humphrey perimetry measurements in subjects with retinitis pigmentosa.
41
42 *Invest. Ophthalmol. Vis. Sci.* 2007;48(10):4720-4.
43
- 44 47. Bengtsson B, Heijl A. Normal intersubject threshold variability and normal
45
46 limits of the SITA SWAP and full threshold SWAP perimetric programs. *Invest.*
47
48 *Ophthalmol. Vis. Sci.* 2003;44(11):5029-34.
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4 48. Hanneman S. Design, analysis and interpretation of method-comparison
5 studies. AACN Advanced Critical Care. 2008;19:223-34.
6
7
8 49. Piñero D, Saenz-González C, Alió J. Intraobserver and interobserver
9 repeatability of curvature and aberrometric measurements of the posterior
10 corneal surface in normal eyes using Schiempflug photography. J Cataract
11 Refract Surg. 2009;35(1):113-20.
12
13
14 50. Armstrong R, Davies L, Dunne M, Gilmartin B. Statistical guidelines for
15 clinical studies of human vision. Ophthal. Physiol. Opt. 2011;31(2):123-36.
16
17
18 51. Prieto L, Lamarca R, Casado A. La evaluación de la fiabilidad en las
19 observaciones clínicas: el coeficiente de correlacion intraclase. Med Clin.
20 1998;110(4):142-3.
21
22
23 52. McAlinden C KJ, Pesudovs K. A comprehensive evaluation of the precision
24 (repeatability and reproducibility) of the Oculus Pentacam HR. Invest
25 Ophthalmol Vis Sci. 2011;29(52(10)):7731-7.
26
27
28 53. Gardiner SK, Johnson CA, Spry PG. Normal age-related sensitivity loss for
29 a variety of visual functions throughout the visual field. Optom Vis Sci. 2006; 83
30 (7):438–443.
31
32
33 54. Maddess, T. The Influence of Sampling Errors on Test–Retest Variability in
34 Perimetry. Invest. Ophthalmol. Vis. Sci. 2012;52:1014-1022.
35
36
37 55. Govert P H, Ponsioen T L, Jansonius N M. Learning effect, normal range,
38 and test–retest variability of Frequency Doubling Perimetry as a function of age,
39 perimetric experience, and the presence or absence of glaucoma. Ophthal.
40 Physiol. Opt. 2003;23:535–540.
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

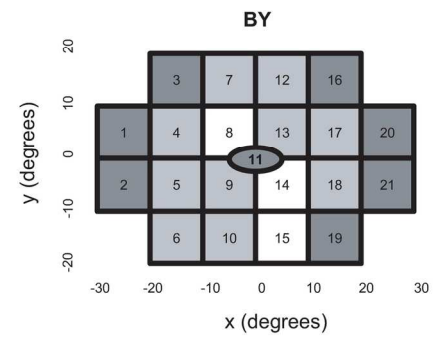
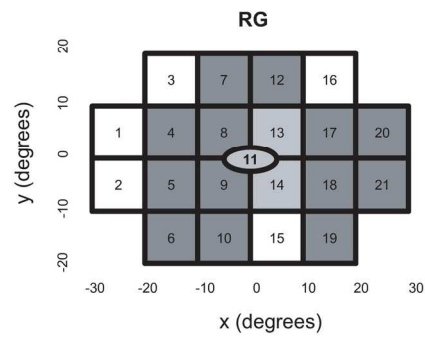
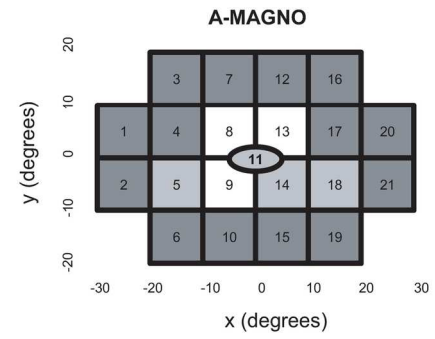
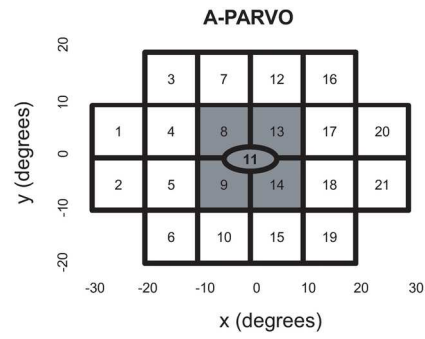
- 1
2
3
4 56. Brainard D. Cone contrast and opponent modulation colour spaces. In
5
6 Kaiser PM, Boynton RM Human Colour Vision Optical Society of America
7
8 Washington DC. 1996:563-79.
9
10
11 57. King-Smith PE, Carden D. Luminance and opponent-colour contributions to
12
13 visual detection and adaptation and to temporal and spatial integration. J Opt
14
15 Soc Am. 1976;66:709–717.
16
17 58. Morilla A, Anton A, Jimenez B, Rodriguez C, Martinez V, Fallon M, Capilla
18
19 P, Luque MJ, Felipe A, Artigas JM. ATD perimetry in glaucoma and ocular
20
21 hypertensive patients. A preliminar study. 10th Congress of the European
22
23 Association for Vision and Eye Research (EVER 2007) pp-64 Abstract book.
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

FIGURE LEGENDS

Figure 1: Results from the repeatability (within-observer) study for each of the 21 testing points in the visual field, for our four stimuli (A-Parvo, A-Magno, RG and BY). The visual field appears divided in $10^{\circ} \times 10^{\circ}$ regions, centered on each testing points, which are coded according to the ICC value or to the result of the Friedman test, as appropriate. ICC: excellent (dark gray), good (light gray). Friedman test: repeatable (white).

Figure 2: Results from the reproducibility (between-observer) study for the 21 testing points in the visual field, for our four stimuli (A-Parvo, A-Magno, RG and BY). The visual field appears divided in $10^{\circ} \times 10^{\circ}$ regions, centered on each testing points, which are coded according to the ICC value or to the result of the Friedman test, as appropriate. ICC: excellent (dark gray), good (light gray). Friedman test: reproducible (white).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

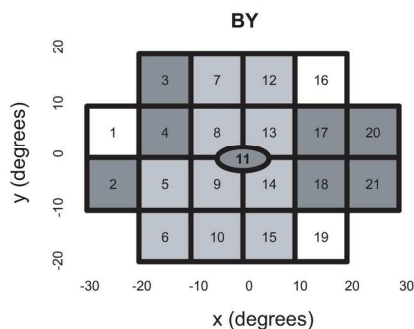
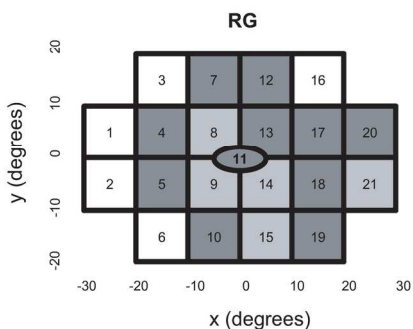
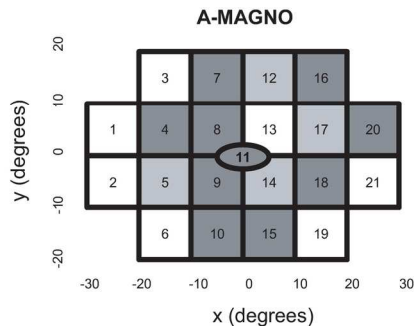
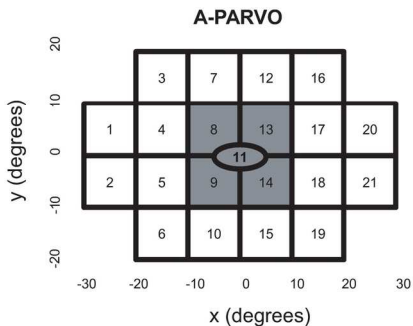


ICC: excellent good

Friedman: repeatable

Results from the repeatability (within-observer) study for each of the 21 testing points in the visual field, for our four stimuli (A-Parvo, A-Magno, RG and BY). The visual field appears divided in 10°x10° regions, centered on each testing points, which are coded according to the ICC value or to the result of the Friedman test, as appropriate. ICC: excellent (dark gray), good (light gray). Friedman test: repeatable (white).
166x132mm (300 x 300 DPI)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



ICC: excellent good

Friedman: reproducible

Results from the reproducibility (between-observer) study for the 21 testing points in the visual field, four our four stimuli (A-Parvo, A-Magno, RG and BY). The visual field appears divided in 10°x10° regions, centered on each testing points, which are coded according to the ICC value or to the result of the Friedman test, as appropriate. ICC: excellent (dark gray), good (light gray). Friedman test: reproducible (white).
166x130mm (300 x 300 DPI)

APPENDIX

Stimuli were generated on a 17 inch LG Flatron F700P CRT monitor, configured to have a horizontal resolution of 1280 lines and a 72 Hz frame rate, driven by a 12-bits video controller (Bits++ , from Cambridge Research Systems). The system was colorimetrically characterized and gamma corrected using the ColorCAL colorimeter and the Cambridge Research Systems Toolbox for MATLAB.

Observers are initially shown a spatially uniform achromatic field, with chromaticity coordinates $x_{CIE}=0.2709$, $y_{CIE}=0.2966$ and luminance equal to 45 cd/m^2 , covering a 60°-horizontal by 40°-vertical fovea-centred area, and are asked to fixate a central 0.5°-wide black cross. The stimuli appearing on this background are flickering achromatic, red-green and blue-yellow gratings, with Gaussian smoothed borders. Testing points are arranged on a 4x6 regular grid –though the four corners of the grid are not tested-, with an additional point at the fovea (see Fig. A1a). Not considering the fovea, the grid spacing is 10° and the offset from the vertical and horizontal meridians is 5°. The stimulus colour is defined by a vector whose components represent the changes in the responses, R, in the achromatic (A), red-green (RG) and blue-yellow (BY) mechanisms of the opponent modulation space^{31,32}, computed using Brainard's formulation⁵⁶. If $\Delta\vec{R}_0$ is the vector in this space defining the direction along which we are measuring the subject's threshold and the amplitude of the stimulus at a given trial and $\Delta\vec{R}(x, y, t)$ is the vector defining the stimulus at each spatial location (x,y), measured (in degrees) from the testing point, at instant t (in seconds) after stimulus onset, we have:

$$\Delta\vec{R}(x, y, t) = \Delta\vec{R}_0 \cdot \sin\left(2\pi f_x x + \frac{\pi}{2}\right) \cdot g(r) \sin 2\pi f_t t \cdot h(t) \cdot \text{rect}\left(\frac{x}{a}, \frac{y}{a}\right) \quad \text{Eq. A.1}$$

where f_x and f_t are the spatial and temporal frequencies of the stimulus, and “ a ” is the angular size of the window containing the stimulus (5°). The functions $g(r)$ and $h(t)$ in Equation A.1 are, respectively, the spatial and the temporal envelope of the stimulus and are defined as follows:

$$g(r) = \begin{cases} 1 & \text{if } 0 \leq r \leq r_0 \\ \exp\left\{-\frac{(r-r_0)^2}{2\sigma^2}\right\} & \text{if } r > r_0 \end{cases} \quad \text{Eq. A.2}$$

where $r^2 = x^2 + y^2$, $r_0 = 1.5^\circ$ and $\sigma = (1/3)^\circ$;

$$h(t) = \begin{cases} \exp\left\{-\frac{(t-t_0)^2}{2\sigma_t^2}\right\} & \text{if } 0 \leq t \leq t_0 \\ 1 & \text{if } t_0 < t \leq T_s - t_0 \\ \exp\left\{-\frac{(t-T_s+t_0)^2}{2\sigma_t^2}\right\} & \text{if } T_s - t_0 < t \leq T_s \end{cases} \quad \text{Eq. A.3}$$

where $T_s = 1$ s is the maximum presentation time, t_0 equals to 100 ms and $\sigma_t = t_0/3$. These functions were introduced to smooth spatial-temporal transients that may constitute a cue for detection by an undesired mechanism.

1
2
3 During a measurement session, the direction of vector $\Delta\vec{R}_0$ is fixed and
4 coincides with one of the three cardinal directions of the space –that is, the
5 direction isolating one of the mechanisms. In Figure A1 we show the limits and
6 directions of the colour palettes in the CIE chromaticity diagram (Fig. A1b), and
7 examples of the spatial and the temporal profiles (Fig. A1c-d), as well as a
8 sample of stimuli in each of the cardinal directions (Fig. A1e-h).
9
10
11
12
13
14
15
16

17
18 **Insert Figure A1 here**
19

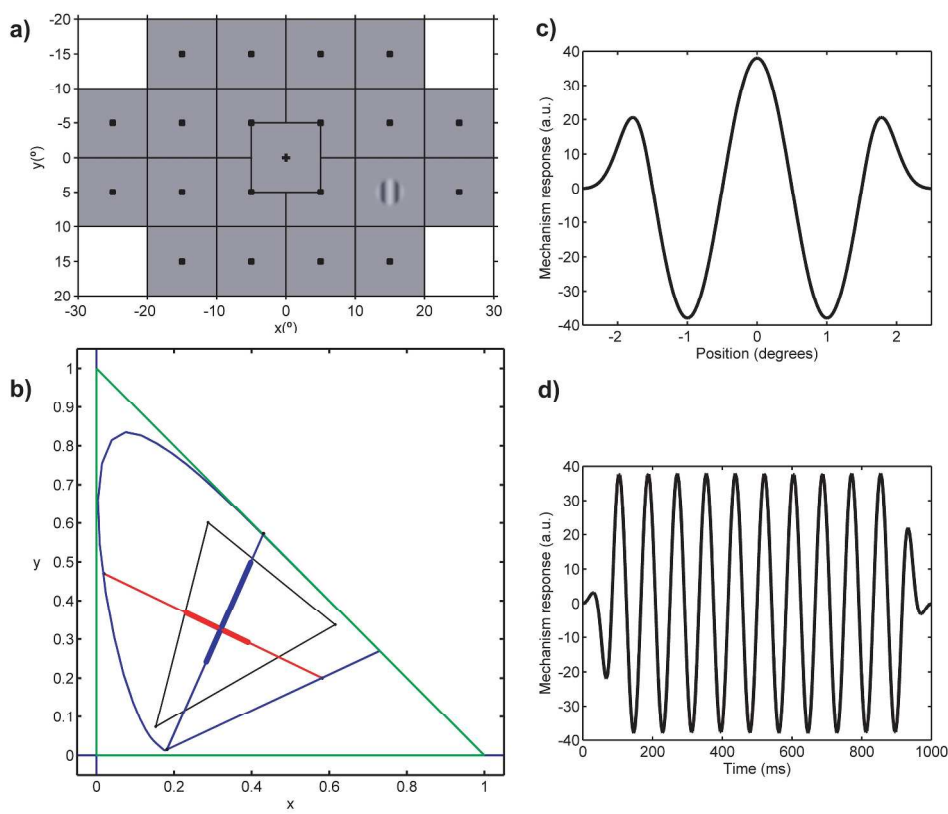
20
21 Stimuli are labelled as “Mechanism (A, RG, or BY)”-“Spatial Frequency
22 (0.5 or 4) in cycles per degree (cpd)” / “Temporal Frequency (2 or 12) in Hertz
23 (Hz)”. To evaluate the achromatic mechanism, a stimulus favouring the
24 magnocellular pathway (A-0.5cpd/12Hz) and another one favouring the
25 parvocellular pathway (A-4cpd/2Hz) were chosen⁴³. The red-green and blue-
26 yellow chromatic mechanisms, putatively mediated by the parvo and
27 koniocellular pathways, respectively⁴³, were evaluated with two stimuli of the
28 same spatial and temporal frequency (RG-0.5cpd/2Hz and BY-0.5cpd/2Hz).
29 The procedure described is similar to the one used by King-Smith for colour
30 contrast thresholds, except for the spatial and temporal profile of the
31 stimulus⁵⁷. The stimuli used in this study were chosen after previous
32 measurements covering the entire frequency range for each mechanism
33 showed that the device had enough dynamic range to determine thresholds of
34 subjects up to 70 years old⁴⁴ and after measurements with pathological subjects
35 suggested the possible utility of these stimuli in detection of functional
36 damage^{33,34,58}.
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

FIGURE LEGEND

Figure A1: (a) Array of testing points, (b) RG and BY cardinal directions in the colour space used in the experiment (CIE1931). The triangle represents the locus of colours generable by the monitor and the thick lines the maximum amplitude range available. (c) Spatial profile of a stimulus as shown in the CRT monitor. (d) Temporal profile of the stimulus. (e–h) Single frame of each of the four stimuli used in the experiment.

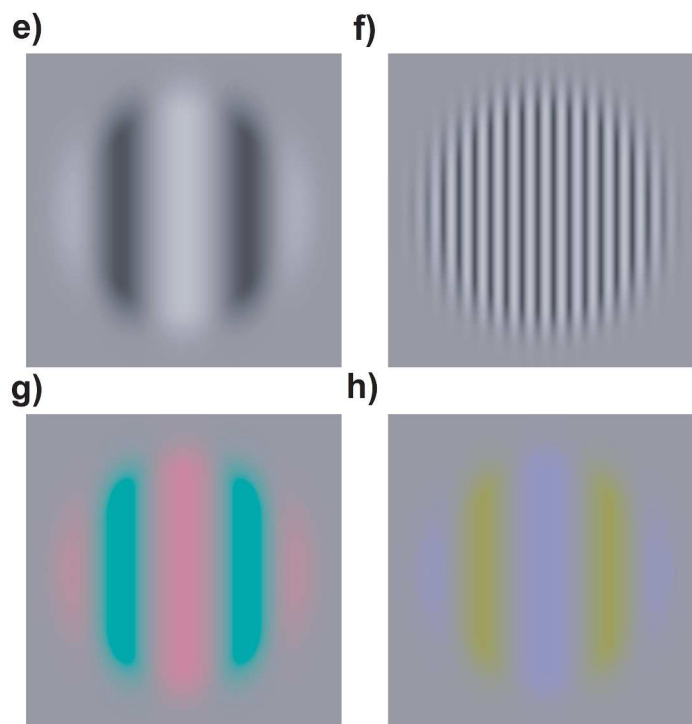
For Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



(a) Array of testing points, (b) RG and BY cardinal directions in the colour space used in the experiment, plotted in the CIE1931 color space. The triangle represents the locus of colours generable by the monitor and the thick lines the maximum amplitude range available. (c) Spatial profile of a stimulus as shown in the CRT monitor. (d) Temporal profile of the stimulus.
274x227mm (300 x 300 DPI)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



(e-h) Single frame of each of the four stimuli used in the experiment.
274x455mm (300 x 300 DPI)