Appendix: An analytic exercise

Assessing visual search in the AFOV test[1]

1. Aim

The AFOV (Attended Field Of View) test aims at assessing the efficiency of visual search (Coeckelbergh et al., submitted). An efficient search strategy is here defined as a strategy that allows the subject to respond to targets in a fast and evenly distributed manner. Hence, the test should provide a measure of general search time as well as a measure of distribution. The mean threshold presentation time (see Methods) is calculated as an estimate of general search time. Two scores to assess the distribution of threshold presentation times across the field of view will be discussed. We will present a measure expressing the 'flatness' and a measure expressing the 'asymmetry' of the distribution. In our opinion, both measures in combination with the mean threshold presentation time give an adequate description of the efficiency of visual search in the AFOV test. By considering these three parameters, typical visual search patterns associated with specific visual field impairments can be differentiated.

2. Methods

The AFOV test makes use of a visual search paradigm. Thirty-one stimuli are presented on a 20-inch screen (stimulus luminance = 40 cd/m^2, background luminance = 16 cd/m^2, room luminance = 500 lux). The stimuli are arranged in three elliptical rings around a central stimulus. The visual angle of this stimulus array is 60 degrees horizontally and approximately 24 degrees vertically. No stimuli are presented on the vertical axis. The subject is sitting in front of the screen at a viewing distance of 30 cm and is instructed to locate an open circle (e.g., C) among 30 closed circles (O) and subsequently indicate the direction of the gap (left, right, top or bottom of the circle). The target can appear at any of 31 positions (Figure 1a). Some positions were pooled and analysed as one position. Figure 1b identifies the pooled data points. All 7 positions on the horizontal axis are analysed as individual data points. Per quadrant three more positions are analysed. Data of the three stimulus elements on the outer ring are pooled, as are the two elements in the middle ring. In this way, six positions are tested per ellipse (Figure 1b).

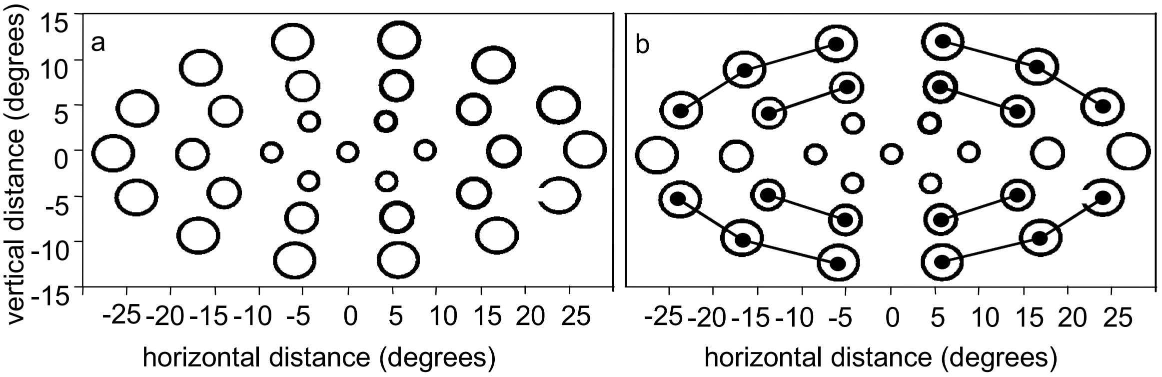

Figure 1a depicts an example of the actual AFOV stimulus as presented to the subject. Figure 1b represents the 19 positions which are analysed. Pooled positions are connected.

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[1] In collaboration with Tanja R.M. Coeckelbergh. This paper is also presented in Coeckelbergh, T.R.M. (2002). Effect of compensatory viewing strategies on practical fitness to drive in subjects with visual field defects caused by ocular pathology. Unpublished doctoral dissertation, University of Groningen, The Netherlands.

The size of the stimulus elements is determined by eccentricity and can be adjusted in relation to visual acuity. Eye and head movements are allowed after the central fixation marker has disappeared (a diamond consisting of four red dots, luminance = 14 cd/m^2). The stimuli are presented with varying presentation times (range: 8ms - 10s). By means of a staircase procedure the presentation time at which the subject can correctly identify the target in 67 per cent of the trials is determined for each of the 19 positions and this is defined as the threshold presentation time. Figure 2 represents the graphical output of the threshold presentation times by a subject with a central field defect. The mean of the 19 threshold presentation times per position is termed the mean threshold presentation time and is considered as an estimate of general search time.

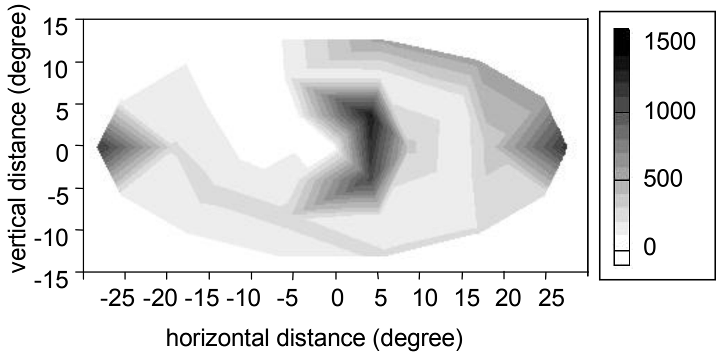


Figure 2. Graphical depiction of AFOV performance by a subject with a central field defect.

3. Requirements of the measure of distribution

In a next step, we wanted to describe the search pattern in terms of its distribution. An even or flat distribution is here defined as a distribution with equal threshold presentation times for all positions. In our view, a distribution score should describe different kinds of distributions and should allow us to compare the distributions directly. It should be easy to interpret and have a limited range. Finally, it should be independent of general search time.

3.1. Different measures for efficiency of distribution

The visual search paradigm of the AFOV test provides a tool to assess scanning behaviour indirectly. Inefficient scanning techniques will cause high threshold presentation times and/or a poor distribution. Scanning behaviour is frequently impaired in patients with visual field defects and can be very diversified. A hemianopic patient, for example, may have an efficient scanning pattern in his intact visual field but a chaotic scanning pattern (if any) in his blind visual field. A patient with tunnel vision may have a slow but structured scanning pattern or a fast but chaotic scanning pattern. These different scanning patterns will lead to different search times and different distributions. In our opinion, a measure of distribution should be applicable for all kinds of visual field defects such as central scotoma, peripheral constriction, quadranopia or hemianopia.

3.2. A limited range and easy to interpret

The measure of distribution should be easy to interpret and its range should be limited, for instance on a scale from 0 to 100. A score of 0 would indicate a flat distribution in which the threshold presentation times are equal for all positions in the field. A score of 100 would be indicative of a search pattern in which the subject performs at the worst level (i.e. responds at the highest presentation times) at half of the positions and at the best level (i.e. responds at the lowest presentation times) at the other half of the positions.

3.3. Unaffected by constant differences across individuals

The measure of distribution should be independent of the absolute value of search time i.e. the mean threshold presentation time and the measure of distribution should be statistically independent. It should be statistically possible to observe a high mean threshold presentation time in combination with a low distribution score and a low threshold presentation time in combination with a high distribution score. This statistical independence between the distribution score and the mean threshold presentation time would result in the same distribution score in case of a subject with high threshold presentation times and a subject with low threshold presentation times but otherwise equal search patterns. Equal search patterns are represented by parallel lines when threshold presentation times are graphically plotted by subject as a function of stimulus position (see figure 3). If the mean threshold presentation time and the distribution score were statistically dependent (i.e. a priori correlated), a slow search strategy (i.e. high mean threshold presentation times) would nearly always result in a high distribution score. As we want to assess and evaluate search time and distribution independently (for example, before and after training), an intertwining of these variables has to be avoided.

3.4. Measures of variability

The distribution of threshold presentation times across all positions in the field of view can be expressed by a measure of variability. A flat distribution characterises low variability indicating that the time needed by the subject to detect the target is approximately the same for every position in the field. Common measures of variability are the range, the standard deviation or the mean absolute deviation. We will briefly discuss these measures, demonstrating their properties and explaining whether or not these properties are desirable for our purposes. To do so, we will use simplified and extreme examples in which data points represent threshold presentation times for several positions in the field. The number of positions and the values are arbitrarily chosen for the purpose of illustration. Plotting the threshold presentation times as a function of their position contributes to the insight of the intuitive notion of distribution (e.g. see figure 3).

Range, the difference between the lowest and the highest score is, for our purpose, not an adequate measure as it does not discriminate between short presentation times on all but one position (subject 1) and e.g. short presentation times on all but three positions (subject 2).

subject 1: 2 2 2 2 2 2 2 2 8 range = 6
subject 2: 8 2 2 2 8 2 2 2 8 range = 6

We consider the distribution of subject 1 as more efficient than the distribution of subject 2 because subject 1 shows only one "peak", whereas subject 2 shows three peaks. This difference should be represented in the distribution measure.

More sophisticated measures, like the mean absolute deviation and the standard deviation, can accommodate this difference in some way and seem thus more appropriate. However, neither the mean absolute deviation, nor standard deviation and derivatives such as the coefficient of variation are suitable for our purpose, as they calculate deviation with respect to the mean. The mean is highly influenced by outliers. As we are particularly interested in the number and value of these extreme scores, we need to avoid a distribution score in which the reference (i.c. the mean) is contaminated by these extremes. We therefore prefer the use of the *median* as a reference to calculate a deviation. The mean absolute deviation with the median as a reference fits our requirements and is represented in the following formula:

$$absolute\ deviation\ from\ median = \frac{\sum |x_i - median|}{n}$$

An example might illustrate this point. Imagine a subject with a right peripheral visual field defect, resulting in the following threshold presentation times:

subject 3: 2 2 2 2 2 2 2 2 80

In our view, the peak of 80 is due to the visual field defect whereas the value of 2 is the baseline value. We presume that if subject 3 would not have had a visual field defect, the distribution would have been completely flat. We therefore prefer to use the median (2) as a reference and not the mean (10.67), because the median more closely reflects the 'real' performance level of this subject. A value of 10.67 seconds would indicate that subject 3 is quite slow in detecting the target, whereas we believe that the subject is actually quite fast (2 seconds) with the exception of one position where the subject cannot perceive the target due to an uncompensated visual field defect.

4. PDM: a measure of distribution

4.1. PDM, percentage deviation from the median

A measure with reference to the median, which is easy to interpret and has a limited range is the PDM, the percentage deviation from the median:

$$PDM = \frac{\left(\frac{\sum |x_i - median|}{n}\right)}{\max deviation} \times 100$$

The deviation from the median of each position (x_i) is calculated, summed and divided by the number of positions (*n*). This score is further divided by the maximum deviation. The maximum deviation is the distribution at which a subject responds at a maximum presentation time at half of the positions and at a minimum presentation time at the other half and is therefore based on a fixed number of positions and a fixed range of presentation times. Finally, the score is multiplied by 100 to fit a range from 0 to 100. A score of 100 indicates that a subject responds at a maximum presentation time at half of the positions and at a minimum presentation time at the other half. This is the worst possible form of distribution. A 0 score is the resultant of equal presentation times across all positions, representing the best possible (i.e. flat) distribution.

In case of the AFOV test with 19 positions and presentation times ranging from 8 milliseconds to 10 seconds, the formula becomes:

$$PDM = \frac{\left(\frac{\sum |x_i - median|}{19}\right)}{4.733} \times 100$$

The maximum deviation is 4.733 and is, as already mentioned, based on a distribution at which a subject responds at a maximum presentation time at half of the positions and at a minimum presentation time at the other half. In case of 19 positions, two situations render the maximum deviation: 10 positions at maximum presentation time and 9 positions at minimum presentation time or vice versa. One of these situations is illustrated below:

data points, representing maximum deviation:
1 1 1 1 1 1 1 1 1 1 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0 0 0 0 0 0 0 0 0 0 8 8 8 8 8 8 8 8 8
median: 10
average mean deviation from median: $\left(\frac{\sum|x_i - median|}{19}\right) = 4.733$

The formula can easily be adapted for different minimum and maximum presentation times and for different number of positions. For example, in case of 5 data points and presentation times ranging from 8 ms to 10 s, two points are set at 10 seconds and three points at 0.008 seconds (or vice versa). In a next step, the average absolute deviation from the median is calculated, as described above. In case of analysing 5 positions of the AFOV test, the maximum deviation would be 3.9968.

4.2. Features of the PDM

4.2.1. Unaffected by constant differences between subjects

The PDM is not affected by constant differences between the threshold presentation times of subjects. Subjects 5 and 6 show the same pattern of distribution but are consistently one resp. three seconds slower than subject 4 (figure 3). As a consequence, their mean threshold presentation time will be different. The PDMs, in contrast, are the same.

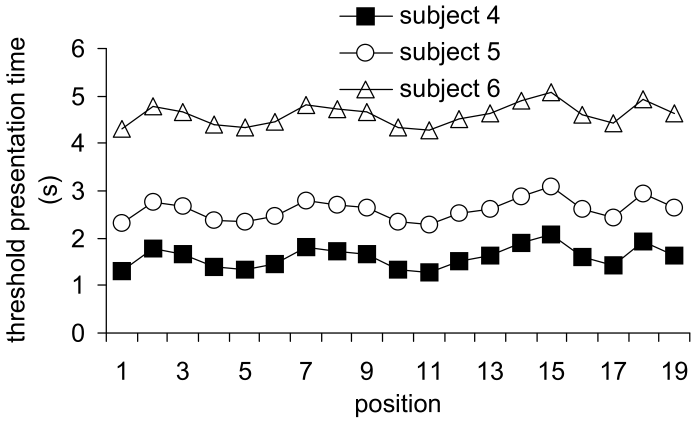


Figure 3. Threshold presentation times of three subjects. Constant differences at every position (represented as parallel lines) between subjects yield different mean threshold presentation times but identical PDMs.

As a consequence, a non-compensating subject with macular degeneration (MD), performing very fast in all areas of the field except the central area will have the same PDM as a non-compensating subject with tunnel vision (RP) who can only perceive the central stimuli (figure 4). The mean threshold presentation times, as an indication of search speed, are different. The PDMs are equal as in both cases only three datapoints deviate from the rest. In the example below, mean presentation time is 2.421 seconds for the MD patient and 8.579 for the RP patient. Median presentation times are 1 second and 10 seconds respectively. PDM is in both cases 30.

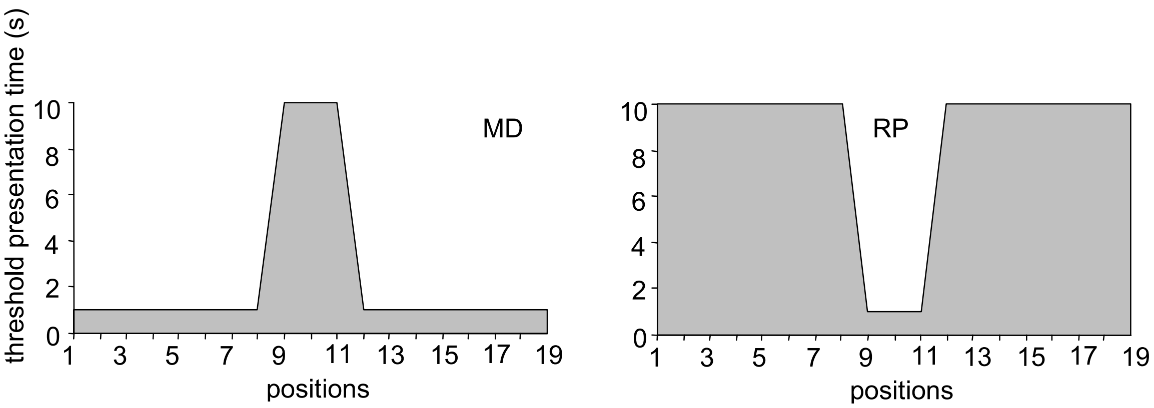


Figure 4. Graphical depiction of the threshold presentation times of a non-compensating subject with MD (left) and RP (right). In both cases the PDM is identical, whereas the mean threshold presentation times are different.

Similarly, the PDM of a hemianopic patient with macular sparing will be equal to the PDM of a hemianopic patient without macular sparing although their mean threshold presentation times will be different. In the example below, mean threshold presentation times are 5.263 seconds (with sparing) and 5.737 (without sparing). Median values are 1 second and 10 seconds respectively. PDM equals 90.07 in both cases.

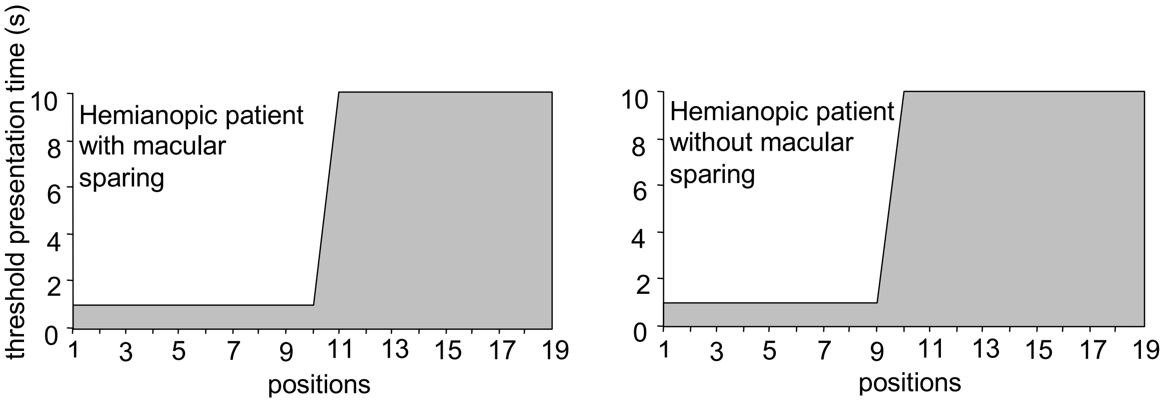


Figure 5. Graphical depiction of the threshold presentation times of a non-compensating subject with right-sided homonymous hemianopia with (left) and without (right) macular sparing. In both cases the PDM is identical, whereas the mean threshold presentation times are different.

4.2.2. Linear relationship between disability and PDM

The PDM scores can easily be compared to each other. A hemianopic patient, missing half of the visual field and not making compensatory eye movements, will not be able to find the target when presented in his blind field. Thus, when not compensating, threshold presentation times will be very high in the affected hemi-field (e.g. 10s). If the patient is very fast in the unaffected field (e.g. performing at minimum presentation times), the PDM equals 100. A quadranopic patient, missing a quarter of the visual field, with the same features (not perceiving targets in the blind field and responding at minimum presentation times in the unaffected field) will have a PDM of 50 which is half of the PDM of the hemianopic patient. This is illustrated in the following example (in case of 8 data points, maximum variability equals 4.996):

hemianopia: 0.008 0.008 0.008 0.008 10 10 10 10
mean: 5.004 *median: 5.004* *PDM: 100*
quadranopia: 0.008 0.008 0.008 0.008 0.008 0.008 10 10
mean: 2.506 *median: 0.008* *PDM: 50*

The relationship between performance in uncompensated hemianopia, missing half of the visual field, and uncompensated quadranopia, missing a quarter of the visual field is thus reflected in the PDM. In the AFOV test with 19 positions, a hemianopic patient would miss 9 or 10 points, resulting in a (averaged) PDM of 100. A quadranopic patient would miss 4 or 5 targets, resulting in an averaged PDM of 50. The ratio equals 2 (100:50=2). This ratio perfectly reflects the degree of impairment since the visual field defect in case of hemianopia is twice as large as the visual field defect in case of quadranopia. In contrast, the standard deviation of this hemianopic patient equals 5.13 and the (averaged) standard deviation of this quadranopic patient equals 4.35, resulting in a ratio of 1.18. This outcome does not correctly reflect the difference in degree of impairment between a (non-compensating) subject with hemianopia and a (non-compensating) subject with quadranopia. Similarly, measurements related to the mean (such as the percentage deviation from mean) result in ratios unequal to 2. As a consequence of the properties of these distribution scores, only the PDM is linearly related to the degree of disability. This is depicted in Figure 6. A (linear) increase in number of deviating points, results in a linear increase in PDM or, in other words, equal steps in degree of uncompensated impairment yield equal steps in PDM. Neither the standard deviation, nor any other measure representing deviation from the mean, hold this linear relationship to the degree of disability.

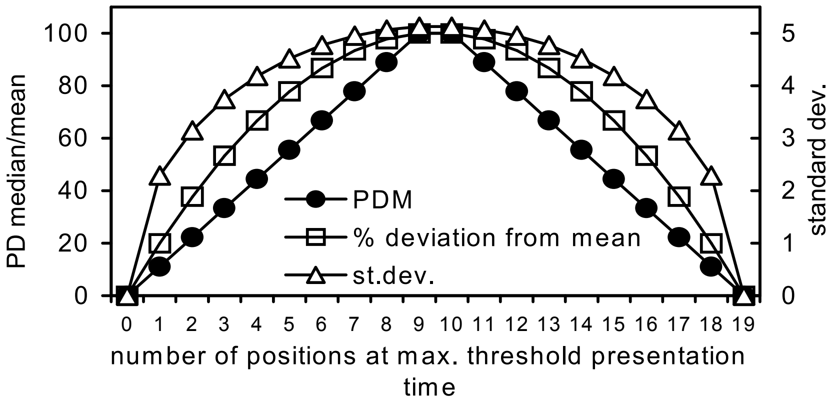


Figure 6. Relationships between degree of disability and measurement of variability. Disability is schematically expressed as the number of positions not seen (i.e. at the maximum presentation time) while the remaining positions are recorded at the minimum presentation times. Only the PDM is linearly related to the degree of disability.

5. Hemi-spatial lateralisation

In the previous sections, a measure of distribution, which is statistically independent of threshold presentation time was presented. It was argued that the PDM provides an adequate measure for expressing ‘flatness’ of the distribution. However, the properties of a search pattern can still be further characterised. This interest in further specification emanates from the desire to specifically describe lateralised performance. Since homonymous visual field defects are a common type of visual field disorder and often result in hemi-spatial disability, lateralised performance can be expected. It is our aim to express this lateralisation, statistically independent of the mean threshold presentation time and the PDM.

A distribution with a high PDM can be the result of both a general scanning deficit (chaotic and ineffective scanning all over the field) and a lateralised scanning deficit (e.g. neglecting a hemi-field). In the first case, the positions of worse performance will be randomly distributed across the search field whereas in the second case, they will be grouped and lateralised. The PDM can not account for this difference, since it is derived from the number of deviating points, irrespective of their location. The measure to be proposed, expresses this lateralisation.

5.1. Required features

Similarly as for the 'flatness' of distribution (i.e. the PDM), we seek an index which expresses lateralised performance, irrespective of the mean threshold presentation time and PDM, with a clearly defined and easy-to-interpret range. It should give an indication of both *degree* and *side* of lateralisation. We will refer to this measure as the Asymmetry Index (AI).

With equal and high PDMs, the AI should differentiate between a totally chaotic distribution (AI=low) and a distribution which is systematic in that worse performance is perfectly lateralised to either left or right hemi-space (AI=high). Equal PDMs and equal AIs should result from completely identically distributed performances or from inverse search patterns such as shown in Figure 4. A non-compensating subject with a central field defect and a non-compensating subject with tunnel vision should produce equal PDMs and equal AIs. Both values should be low in these examples; the mean threshold presentation times will differentiate both cases. It was previously shown that the PDM differentiates uncompensated hemianopic performance from e.g. quadranopic (but otherwise equivalent) performance. However, in spite of different PDMs, both types of search behaviour are similar in that they are perfectly lateralised. Hence, the asymmetry index should give identical and high values.

Not only the *degree* of lateralisation but also the *side* of lateralisation should be represented by the asymmetry index. The degree of lateralisation will be expressed by the absolute value whereas of the AI the side of lateralisation will be indicated by its sign. Hence, the range of the AI will vary from -1 to +1, indicating respectively extreme lateralisation to left and right hemi-space. No lateralisation (AI=0) results from e.g. only central impairment. Additionally, when the threshold presentation times at homologous stimulus positions are identical or in case of a completely unsystematic distribution, AI will equal 0. Hence, in the previous discussion, a *low* AI should be paraphrased as *tending to 0* and a *high* AI would be *tending to either -1 or +1*.

5.2. The Asymmetry Index

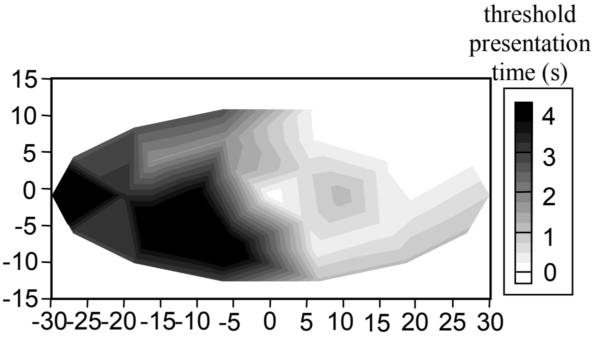
It was previously described that in this version of the AFOV test, 19 different locations can be analysed (see Methods section). Except for the centre location, all other 18 points are situated either in the left or right hemi-space (nine points each) (see Figure 1). To express lateralisation, we will calculate the asymmetry index as:

$$AI = \left[\frac{\left(\overline{X}_{right\ hemispace} - \overline{X}_{left\ hemispace}\right)}{\left(\overline{X}_{right\ hemispace} + \overline{X}_{left\ hemispace}\right)} \right]$$

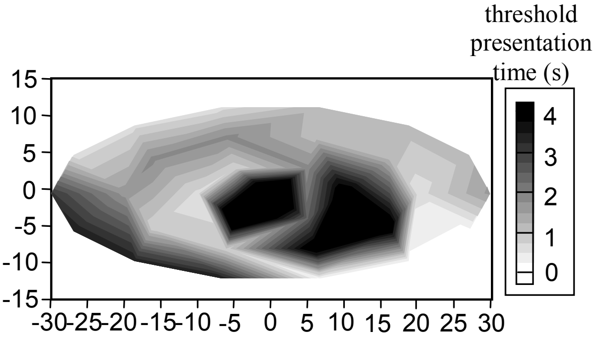
where $\overline{X}_{hemispace}$ indicates the mean presentation time of the nine locations in the respective hemispace. This index varies from -1 to +1, and is statistically independent from absolute search time and PDM. It further produces identical values for all types of complementary search patterns (e.g. MD vs. RP) and uncompensated hemi-spatial disability (e.g. hemianopia vs. quadranopia).

5.3. Examples

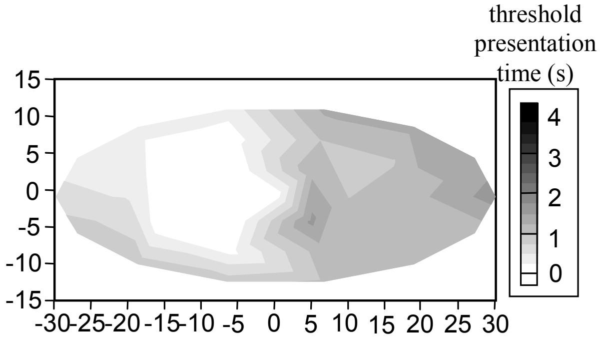
The examples below are AFOV performances by patients with left-sided homonymous hemianopia (subjects 1-2, 4) and right-sided homonymous hemianopia (subject 3). Although these subjects have similar visual field defects, their scanning behaviour, as measured by the AFOV test, clearly differs.



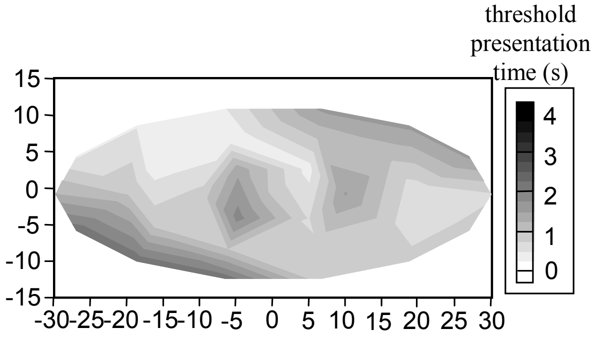
Subject 1: Graphical depiction of AFOV performance by a left-sided hemianopic patient. This performance results in a high PDM and a high AI.



Subject 2: Graphical depiction of AFOV performance by a left-sided hemianopic patient. This performance results in a high PDM and a low AI.



Subject 3: Graphical depiction of AFOV performance by a left-sided hemianopic patient. This performance results in a low PDM and a high AI.



Subject 4: Graphical depiction of AFOV performance by a left-sided hemianopic patient. This performance results in a low PDM and a low AI.

We illustrate the four different combinations of high (grey) and low PDMs and AIs.

	Subject 1	Subject 2	Subject 3	Subject 4
Mean Threshold Presentation Time (s)	1.87	3.00	0.75	1.21
PDM	29	36	10	8
AI	-0.71	-0.08	0.56	-0.12

In the AFOV test as presented, performance can thus be evaluated using three different and statistically independent measures. The mean threshold presentation time indicates general search time. The PDM provides an indication of the 'flatness' of distribution across the search field. The AI provides a measure of hemi-spatial lateralisation.