

Characteristics of dynamic processing in the visual field of patients with age-related maculopathy

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Abstract

Purpose To investigate the characteristics of dynamic processing in the visual field of patients with age-related maculopathy (ARM) by measuring motion sensitivity, double-pulse resolution (DPR), and critical flicker fusion.

Methods Fourteen subjects with ARM (18 eyes), 14 age-matched controls (19 eyes), and 7 young controls (8 eyes) served as subjects. Motion contrast thresholds were

determined by a four-alternative forced-choice (4afc) staircase procedure with a modification by Kernbach for presenting a plaid (size=3.8°) moving within a stationary spatial and temporal Gaussian envelope in one of four directions. Measurements were performed on the horizontal meridian at 10°, 20°, 30°, 40°, and 60° eccentricity. DPR was defined as the minimal temporal gap detectable by the subject using a 9-fold interleaved adaptive procedure, with stimuli positioned on concentric rings at 5°, 10°, and 20° eccentricity on the principal and oblique meridians. Critical flicker fusion thresholds (CFF) and the Lanthony D-15 color vision test were applied foveally, and the subjects were free to use their fovea or whatever retinal area they needed to use instead, due to their retinal lesions caused by ARM. All measurements were performed under photopic conditions.

Results Motion contrast sensitivity in subjects with ARM was pronouncedly reduced (0.23–0.66 log units, $p < 0.01$), not only in the macula but in a region up to 20° eccentricity. In the two control groups, motion contrast sensitivity systematically declined with retinal eccentricity (0.009–0.032 log units/degree) and with age (0.01 log units/year). Double-pulse thresholds in healthy subjects were approximately constant in the central visual field and increased outside a radius of 10° (1.73 ms/degree). DPR thresholds were elevated in subjects with ARM (by 23–32 ms, $p < 0.01$) up to 20° eccentricity, and their foveal CFFs were increased by 5.5 Hz or 14% ($p < 0.01$) as compared with age-matched controls.

Conclusions Dynamic processing properties in subjects with ARM are severely impaired in the central visual field up to 20° eccentricity, which is clearly beyond the borders of the macula.

Keywords ARM · Contrast sensitivity · Motion perception · Temporal resolution · Visual field

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Introduction

Age-related maculopathy (ARM) is the most common cause of loss of central vision in industrialized countries [17, 26, 30, 33, 34, 62]. Almost all clinical assessments of the consequences of ARM for basic visual functions and quality of life refer to foveal or macular vision. However, a few studies have shown that retinal defects can occur beyond 10° eccentricity, which can be considered the maximum radial extent of the macula. Sunness et al., for instance, described histopathological anomalies outside the central retina, whereas sensitivity was unchanged in traditional static perimetry [55].

Curcio et al. described that, beyond general age-related photoreceptor loss, five out of six ARM-affected donor eyes showed cone and rod loss in parafoveal regions [12]. The latter can be expected to reduce dark adaptation performance, which was confirmed up to 25° eccentricity by Brown et al. [9]. In addition, ARM affects temporal aspects of visual information processing. Mayer et al. found reduced temporal resolution of ARM patients as measured by foveal flicker sensitivity with a stimulus of 2.8° diameter [40, 41]. Brown and Lovie-Kitchin showed reduced flicker resolution in the fovea and at 10° and 20° eccentricity and concluded that “the functional effects of ARM are not confined to the central retina, but affect a large region of the visual field” [11]. Falsini et al. found cone-mediated flicker sensitivity (CFS) losses in ARM by evaluating the focal electroretinogram (FERG) as a function of flicker modulation depth in the macula (9° radius) [13].

In summary, the results of these studies show age-related as well as ARM-related functional loss of dynamic processing. However, whether the loss is confined to the macula has not been definitively answered. A further question is whether a loss outside the macula is specific to temporal resolution or whether other temporal aspects of retinal processing, such as motion sensitivity, can also be affected beyond the macula in patients suffering from ARM. Furthermore, we asked whether the impairment is confined to the magnocellular system or also involves the parvocellular pathway.

Methods

Motion contrast threshold

Experimental setup

The experimental setup allowed measurements of peripheral motion perception up to 60° eccentricity under photopic conditions (luminance=75 cd/m²). It consisted of a white, semicircular (180°) plastic screen (radius 90 cm, height

60 cm) with a rectangular opening in the center. A flat-screen LCD display was mounted behind the opening for the presentation of the test patterns. The subjects sat in front of the screen at a distance of 90 cm and monocularly fixated one of the fixation marks in primary view (fixation crosses with diameter=4 cm and bar width=0.5 cm). The marks were attached to the plastic background at 10°, 20°, 30°, 40°, and 60° eccentricity (Fig. 1). Fixation was monitored by a mirror mounted below the LCD display. Thus, the examiner could monitor the subject’s eye movements during the presentation of a stimulus. Additionally, the mirror could be moved horizontally to allow a clear view of the patient’s eye, even in extremely peripheral positions. We are confident that the examiner was able to detect saccadic eye movements of at least 5° amplitude, which is still only half of the distance between two measuring locations.

Monitor calibration

To achieve specified stimulus luminance and contrast, the monitor’s gamma curve (screen luminance vs. gray value) needs to be taken into account during stimulus presentation [4, 51, 52, 54]. We measured this for our monitor using Intel’s PXL software to set the screen uniformly at the 256 possible gray levels and measured center screen luminance with a digital luminance meter (Gossen Mavomonitor G04068, Nürnberg, Germany) [25]. A second order function was fit to the luminance data by non-linear regression ($r^2=99\%$):

$$L = 4.807 - 0.1887g + 0.0034g^2,$$

where L is center screen luminance in cd/m² and g is the uniform gray value (range 0–255). These function parameters are incorporated in our stimulus presentation software

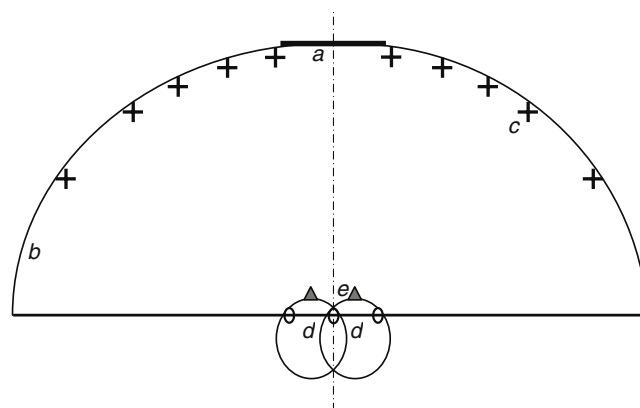


Fig. 1 Experimental set up (top view). The subject’s chair was rotated to maintain primary gaze for all tested fixation marks. **a** LCD monitor screen. **b** Semicircular plastic screen. **c** Fixation crosses (diameter=4 cm, bar width=0.5 cm). **d** Chin rest for stabilizing the head and keeping the viewing distance constant. **e** Subject’s right or left eye

(see below). Target contrast is specified in the Michelson measure, $((L_1 - L_2)/(L_1 + L_2))$.

Design of the motion stimulus

The test software for motion perception was custom-developed for these experiments and consists of two separate modules, one for stimulus generation and another for running the actual test program. Since threshold measurements are much faster and more reliable using four-alternative forced choice than two-alternative forced choice tasks, we employed four directions of motion (up, down, left, and right) to be discriminated by the subject. The stimuli were plaids composed of two orthogonal Gabor patterns of 45° left and right tilt [15]:

$$L(x, y, t) = e^{-\frac{x^2+y^2}{\sigma_r^2}} \cos(\omega x + \varphi_x(t)) \cdot \cos(\omega y + \varphi_y(t)) + L_0$$

$$= e^{-\frac{x^2}{\sigma_x^2}} \cos(\omega_x x + \varphi_x(t)) \cdot e^{-\frac{y^2}{\sigma_y^2}} \cos(\omega_y y + \varphi_y(t)) + L_0$$

where L and L_0 are the luminances of pattern and background, respectively, $\sigma_r^2 = \sigma_x^2 + \sigma_y^2$ is the square of radial diameter of the Gaussian envelope (the value where the amplitude has decreased to $1/e$), and $\varphi(t)$ is the spatial phase at time t (i.e. the shift within the envelope). For the plaids used here, we chose $\sigma = 0.8$, which results in about 1.5 visible cycles (Fig. 2).

The subject's task was to identify the direction of motion. Watson found that thresholds of motion detection and motion discrimination in healthy subjects are equal at sufficiently low spatial frequencies (e.g. 2 cpd) for both slow (1.5 Hz) and fast (12.4 Hz) movement of the test

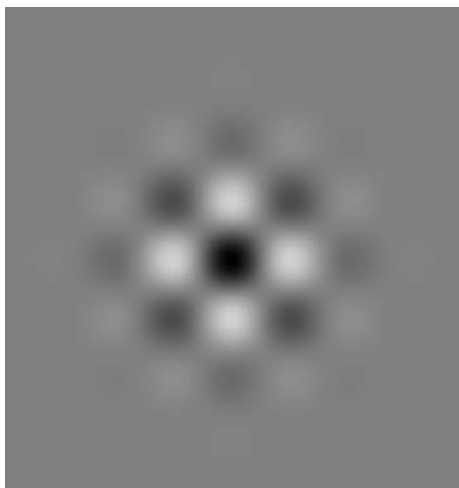


Fig. 2 Gabor stimulus with double sinusoidal modulation in spatial quadrature. The entire patch was stationary, while the plaid pattern moved within the envelope in one of four possible directions. In addition, the stimulus was temporally modulated by a Gaussian envelope function, so that it slowly appeared out of the medium grey background and then merged back into it

pattern [63]. Therefore, we used a low spatial frequency of 0.65 cpd and an intermediate speed of 5.71 °/s (corresponding to 3.75 Hz local luminance change) for the motion stimulus. The size of the test pattern at the viewing distance of 90 cm was 3.8°. To minimize attracting transient attention by abrupt pattern onset, the test pattern gradually appeared and disappeared by using a Gaussian temporal envelope [27, 36, 37]. Due to the small changes between frames in these stimuli, “tearing” of the image was extremely unlikely and was indeed never observed [16].

Adaptive algorithm

Monocular contrast thresholds for motion perception were measured along the horizontal meridian in the nasal and temporal visual field at 10°, 20°, 30° and 40° eccentricity and in the temporal visual field additionally at 60°. The initial contrast value for all eccentricities was 30% (1.48 log %-contrast). For each eccentricity, the threshold was determined twice. Two blocks of nine measurements each were taken and the arithmetic mean calculated from the two results. The adaptive algorithm for threshold determination was based on Kesten and was modified according to Kaernbach to allow the additional response alternative “I don't know” [28, 29, 32, 58]. This paradigm, termed “unforced choice task” by Kaernbach, has been shown to be beneficial, especially for subjects who are unfamiliar with psychophysical testing procedures.

Kesten's algorithm is of the staircase kind, i.e. the intensity of the next presentation depends on the previous response only, not on the entire history or a longer sequence of preceding responses [32]. After a correct response, the log contrast of the stimulus was decreased by one incremental step, and after an incorrect response, it was increased by 1.67 incremental steps (5/3). It thereby converged on the 62.5%-correct point (5/8), i.e. the point of inflection φ on the psychometric function (of log contrast) in a four-alternative forced-choice task. The ratio $V=5/3=1:1.667$ of up-down intensity changes results from Kesten's algorithm given the number n of response alternatives (four) by

$$V = \frac{\phi}{1 - \phi} = \frac{5/8}{3/8} = \frac{5}{3}$$

where ϕ is the probability at threshold or point of convergence,

$$\phi = \frac{1 + \gamma}{2}$$

with guessing rate $\gamma = 1/n = 1/4$. (c.f. Treutwein's equation 16, the last term $(Z_n - \varphi)$ [58]). When the subject gave the indecisive response “I don't know”, the intensity of the next stimulus was increased by one incremental step, as specified by Kaernbach's extension which requires the specification of

V as above [28]. The step width in Kesten's algorithm is reduced by a factor of $m/(m+2)$ after a change in response category (correct-to-incorrect or vice versa) where m is the number of reversals (Treutwein's eq. 16). Since Kaernbach's extension requires the above-mentioned fixed ratio of up-down intensity changes, we used a step width reduction only every other reversal (i.e. m even). The Kesten rule is applied to log contrast, i.e. $\log C_{n+1} = (\log C_n) \pm s_n$ (where s_n is the step width), which is equivalent to contrast being multiplied or divided by the antilog of step width.

Double-pulse resolution

Treutwein and Rentschler developed a hardware and software combination for the measurement of double-pulse resolution (DPR) which allows simultaneous measurement at multiple visual field positions [60]. The technique has been used in experiments on patients with multiple sclerosis and glaucoma, and in an extensive study characterizing the temporal properties of the visual field across the life span [46, 48–50]. The experimental setup allowed (limited by screen size) measurement of DPR up to 20° eccentricity, i.e. not as far into the periphery as for the motion contrast thresholds but well beyond the macular region.

Test setup

An analogue 15" x-y-z display was used for stimulus presentation (Hewlett Packard model 1310, i.e. a CRT-display without a raster-scan generator), driven by a temporary buffer that stores the point coordinates and generates the control voltages for the display ("point plot buffer"; G. Finlay,

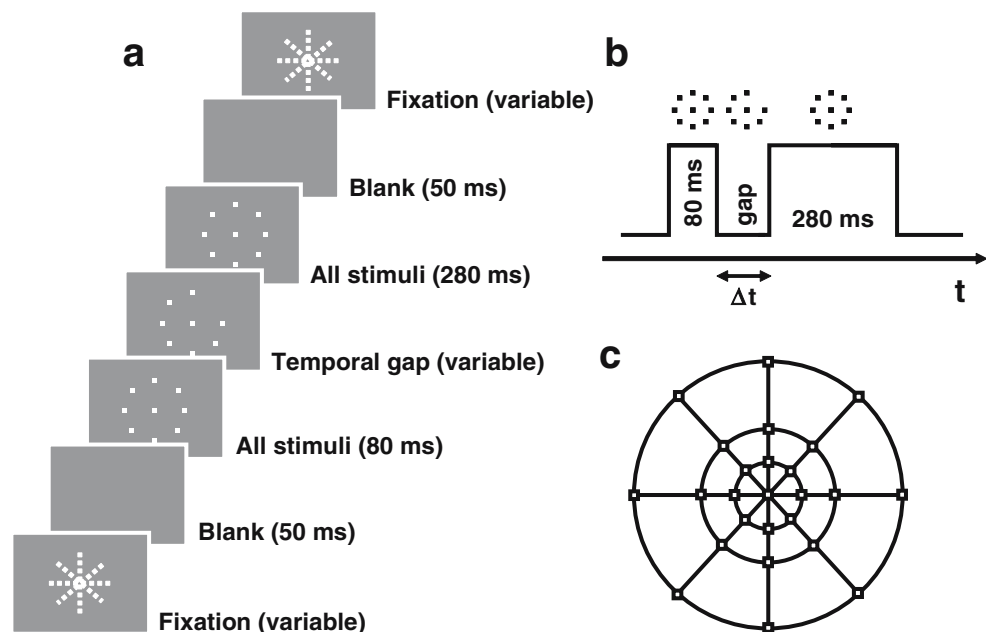
Edmonton, Canada). Temporal control could be extended into the low microsecond range, so that the temporal resolution was better by a factor of 1,000 than in conventional setups [60]. A computer (PC) was used for running the experimental software that controlled stimulus generation, adaptive procedure, and data acquisition. The experimenter recorded the subject's responses via the computer keyboard.

Stimulus characteristics

The tests were performed monocularly at 30 cm viewing distance with a diagonal screen diameter of 40 cm. The stimuli in Treutwein's technique are eight squares of $1.15^\circ \times 1.15^\circ$ visual angle (5×5 pixels) each, arranged in circles at 5° , 10° , and 20° eccentricity around a ninth square in the center [60]. Figure 3 shows the stimulus time course. Eight of nine squares are continuously present for $80 + \gamma + 280$ ms. The target, one randomly selected stimulus, is switched off after 80 ms and then on again after a variable time gap γ . The subject's task was to detect the gap and indicate the target position on the screen, which makes it a nine-alternative forced choice task. In supra-threshold trials, its location can be recognized as a short flicker of the target. A central fixation cross was presented continuously between stimulus presentations and was switched off 50 ms before the beginning of a new trial. The squares' luminance was 215 cd/m^2 ; subjects were light-adapted and the display background luminance was held constant in the low photopic range (luminance $\sim 15 \text{ cd/m}^2$).

Gap duration was varied by an adaptive thresholding algorithm ("YAAP"), based on maximum-likelihood psychometric function fitting [20, 59].

Fig. 3 Double-pulse stimulus characteristics (figure modified after Poggel and Strasburger, originally from Treutwein and Rentschler [46, 60]). **a**, **b** Time line diagram of stimulus display. **c** Stimulus positions (5° , 10° , and 20° eccentricity)



Flicker frequency analyzer

For measurement of foveal flicker fusion frequencies we used the “Wiener Testsystem”, a commercial computer-based diagnostic system with an emphasis on assessing driving fitness (Schuhfried, Moedling/Vienna, Austria). The system was chosen as a reference, because it is an established standard system in Germany used for psychological testing; due to its construction it allows foveal measurement only. Measurements were performed by presenting a circular flickering red light stimulus (1.2° diameter; luminance=270 cd/m²; wave length 655 nm) on a white background in a tubular viewer. Thresholds were determined by the method of limits, i.e. the frequency of the flickering light is increased until permanent light is perceived and is then decreased until the light is once again perceived as flickering.

The subject indicated the perceived changes by a keystroke whereupon the critical frequency was recorded. The separate arithmetic means of the critical frequencies determined in the ascending and descending series are referred to as fusion frequency and flicker frequency, respectively. Each test cycle consisted of five training cycles, immediately followed by eight measurement cycles. For further analysis, the mean of the fusion frequency and the flicker frequency was calculated for each subject, which is referred to as the critical flicker fusion frequency (CFF).

Color perception

The Lanthony D-15 color vision test (desaturated) was used for the examination of color perception. The test consists of 15 colored chips, which are used to determine the subject's capability to discriminate hues. At 50 cm viewing distance, every chip has a diameter of about 1.5°. The subject sorts the arbitrarily shuffled chips according to the arrangement in the color cycle. The chosen sequence was then documented in a test protocol and the color confusion score (CCS) and crossings over the color space were determined [1]. The measurement was done once under constant lighting conditions (color temperature ~4000 K).

Subjects

We recruited three groups of subjects for this study: 14 subjects with ARM (19 eyes, mean visual acuity: 0.29, SE±0.048; ~20/63), a control group of age-matched subjects with healthy eyes (14 subjects; 18 eyes, mean acuity: 0.65, SE±0.057; ~20/32), and another control group of 7 young subjects (8 eyes, mean acuity: 1.25, SE±0.047; 20/16) (Table 1). ARM in 16 of the 19 eyes of patients were classified as “dry” and three as “wet”. Six of 19 eyes in the ARM group had received intra-ocular lens implants during cataract surgery, which was also the case for 14 out of the 18 eyes of the age-matched control group. Since in most cases the implant causes mild myopia (−0.5 dpt), the patients-though presbyopic-could observe the fixation mark comfortably without near correction. Thus, optical artifacts from eye-glasses were prevented, such as aberrations or interference from the glasses' rims, which would otherwise occur at higher eccentricities.

Visual acuity (VA) was measured by a Landolt ring test (Binoptometer, Oculus, Germany) at 90 cm viewing distance ($VA=1/\omega'$, where ω' is the minimum angle of resolution in minutes). Based on these values, all subjects were capable of directing their gaze at the fixation mark without glasses. All subjects with ARM and the age-matched control group provided an up-to-date medical statement from an ophthalmologist, which appraised the condition of the retina and excluded other eye diseases (e.g. glaucoma, secondary cataract). All subjects were examined by their ophthalmologist with respect to clarity of the optical media, and none of them showed any evidence of changes in the visual pathways.

The complete examination (including the initial interview) took approximately 3 hours.

The ages of the subjects with ARM and the age-matched controls were sufficiently close; a t-test with a preceding test for normal distribution showed that the two groups did not differ significantly with respect to their age ($p=0.36$). The study design had been approved by the ethics committee of the University of Munich and testing procedures were in accordance with the tenets of the Declaration of Helsinki. All subjects gave their informed consent for participation.

Table 1 Age and visual acuity of the subject groups

	N	Age		Visual acuity		Mean	SE
		Mean	SE	Minimum	Maximum		
ARM group	19	73.79	2.3	60	90	0.29 (20/63)	0.048
Age-matched controls	18	71.5	1.5	60	78	0.65 (20/32)	0.057
Young controls	8	27.1	1.7	21	34	1.25 (20/16)	0.047

Visual acuity is described in decimal notation and Snellen fractions

Results

Motion contrast threshold

Figure 4 shows the contrast thresholds for motion perception as a function of eccentricity in the visual field. Compared with the age-matched controls, the ARM group shows a distinct increase of contrast thresholds up to 20° in the nasal and up to 40° in the temporal field. Mann-Whitney U-tests of the contrast thresholds at 10°, 20°, 30°, and eccentricity on the horizontal meridian each showed significant differences between the two elderly groups (Table 2).

Double-pulse resolution

With respect to double-pulse resolution, the subjects with ARM showed strongly increased thresholds compared with the age-matched controls within the 20° visual field covered by the test area (Fig. 5). For better comparison with the motion sensitivity data, Fig. 6 also shows the double-pulse results on the horizontal meridian. Both the comparison on the two horizontal meridians and on the entire circles at the investigated eccentricities (5°, 10°, and 20°) show significant group differences. We performed a Mann-Whitney U-test at every position on the horizontal visual field meridian (Table 3).

Critical flicker fusion frequency (CFF)

Figure 7 shows critical flicker fusion frequency (CFF) as a function of age for the three subject groups. There is a slight but significant ($p < 0.05$) loss of CFF with age. It amounts to 0.059 Hz per year of age (i.e. around 5 Hz for the entire life span), which accounts for 30% of the inter-individual variance in the healthy subjects. Age-independent

interindividual variance (70%) thus far exceeds the age-related loss. More importantly here, however, the graph also shows the marked loss of performance in the subjects with ARM. On average, the CFF in the ARM group is lower by 5.47 Hz, or approximately 14%, in comparison to the age-matched controls. Note that one 90-year-old subject reached the level of young normal subjects, while all other subjects with ARM showed lower performance than all young controls.

The analysis of variance (one-way ANOVA with group as factor and post-hoc test, Tamhane procedure) indicates a highly significant difference between the three groups ($F = 25.16$; $df = 2$; $p < 0.001$) which was caused predominantly by the highly significant difference between the age-matched control group and the ARM group ($p < 0.001$).

Color perception

Performance in color perception is a sensitive indicator of differential impairment of the parvo- vs. the magnocellular system [31]. The result from the Lanthony D-15 color vision test (unsaturated) allows the calculation of the color confusion score (CCS), which was used for the statistical analysis of the results. A one-way ANOVA with subject groups as factor and subsequent post-hoc test (Tamhane procedure) showed highly significant differences ($F = 25.285$; $df = 2$; $p < 0.001$) between the three test groups. The difference between the age-matched control group and the ARM group was also highly significant ($p < 0.001$). Thus, the subjects with ARM clearly showed impaired color discrimination. The comparison of crossings over the color space also shows significant differences between the subject groups ($F = 20.394$; $df = 2$; $p < 0.001$; mean crossings: ARM=5.81, age-matched controls=1.78, and young controls=0).

Fig. 4 Mean contrast thresholds for motion perception of the subjects with ARM, age-matched controls, and young controls on the horizontal meridian. The *broken lines* show the increased contrast thresholds when stimuli were presented near the blind spot. The *continuous lines* show the regression (specified in the formula); omitted for the age-matched control group on the temporal side for clarity

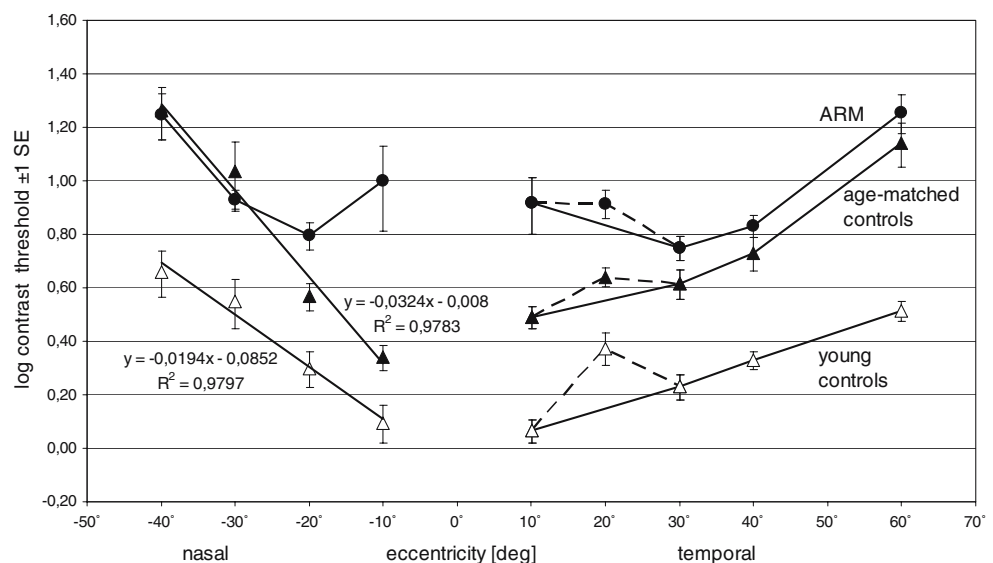


Table 2 Results of Mann-Whitney U-tests of contrast thresholds (ARM group vs. age-matched control group); *U* is the statistical value of non-parametric Mann-Whitney test for comparison of independentsamples based on ordinal ranks; *z* is the estimated statistical value of normalized distribution of *U* values; *p* is the significance level

Eccentricity	Nasal field			Temporal field		
	<i>U</i>	<i>z</i>	<i>p</i>	<i>U</i>	<i>z</i>	<i>p</i>
10°	16.00	-4.71	<0.001	53.00	-3.59	<0.001
20°	69.50	-3.09	0.002	72.50	-2.83	0.005
30°	148.50	-0.68	0.49	96.00	-2.28	0.023
40°	145.50	-0.25	0.80	102.00	-2.10	0.036
60°	–	–	–	134.00	-1.12	0.261

Discussion

Motion perception

Our findings document deficits of dynamic visual field properties in ARM in a retinal region that extends far beyond the macula. In a sense, the well documented loss of visual function (e.g. foveal acuity) in the macula of subjects with ARM seems just like the proverbial tip of an iceberg. To our knowledge, this is the first study of dynamic characteristics of the peripheral visual field up to 60° eccentricity in subjects with ARM. Functional studies on these patients in the past have either concentrated on foveal function only, or have used a large central stimulus that did not discriminate between foveal and nonfoveal function [5, 40–42, 57]. Only the study by Brown and Lovie-Kitchen has shown deficits in the temporal visual field up to 20° eccentricity [13].

There are only a few studies on dynamic processing characteristics in ARM. Mayer et al. measured flicker sensitivity only foveally and suggest that it can be a predictor of exudative ARM [40, 41]. Normal aging

of visual function – from which ARM losses need to be distinguished – has received only limited attention [19, 45, 46, 61].

In the present study, we determined the contrast thresholds for motion perception far into the periphery of the visual field on the horizontal meridian, up to 40° on the nasal, and 60° on the temporal side. We found pronounced impairment in the ARM group up to 20° nasally and 30° temporally, and smaller impairments still further out on the temporal side. The macula is commonly described as having a radius of 10° [2, 22]. These elevated contrast thresholds for motion perception extend far beyond this eccentricity, in conflict with a widespread assumption that the effects of manifest ARM are restricted to the macula. The latter seems to be based on two facts. First, customary descriptions and classifications of the disease use morphological features that are visible by ophthalmoscopy or on fundus photographs [6–8]; and second, many experimental studies have tested vision in subjects with ARM only in central locations in the visual field as noted above, with a few notable exceptions [10, 11, 55].

Fig. 5 Mean double-pulse resolution (DPR) of the ARM group, age-matched controls and young controls at 5°, 10°, and 20° eccentricity (stimuli positioned on concentric rings, Fig. 3). The 0°-value represents the foveal DPR in the 5°-ring measurement. Note that the rather small SEM error bars indicate a limited range of variation of values

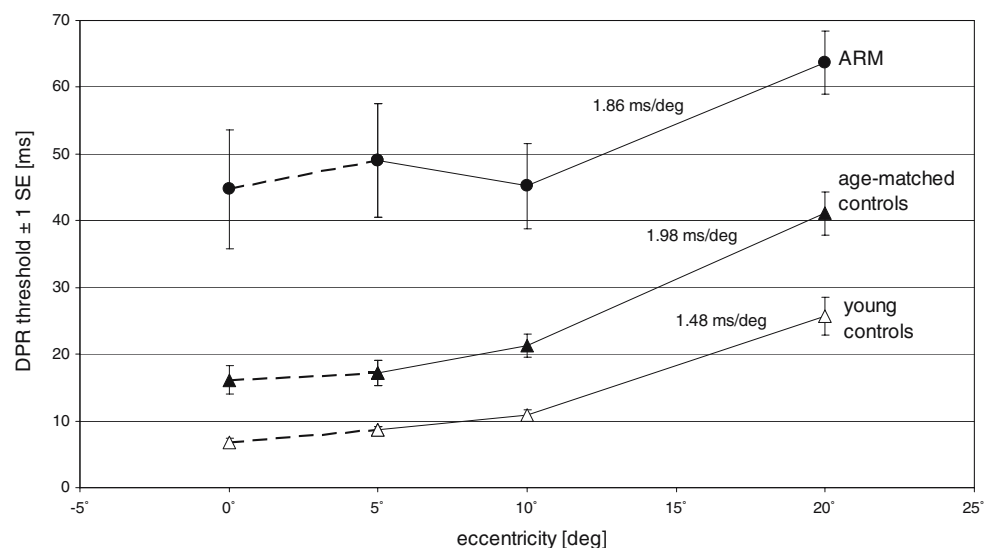
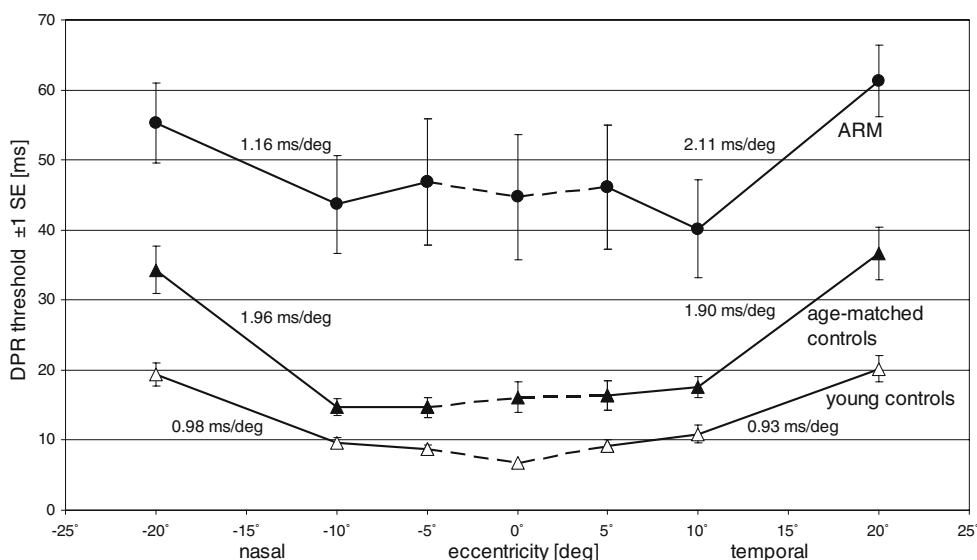


Fig. 6 Double-pulse resolution (DPR) of the ARM group, age-matched controls, and young controls along the horizontal meridian



In clinical practice, the assessment of the visual periphery is believed to play a minor role in ARM, for a lack of consequences in ophthalmic treatment and also because of the dramatic vision loss from damage to the central retina, immediately noticed by patients who report the loss of the ability to recognize fine spatial or contrast detail (e.g. small print). A loss of peripheral motion sensitivity, in contrast, is not easily recognized by the patient, possibly because the conscious (sustained) component of attention is normally directed towards central vision, whereas the transient (reflex-like) component of attention is not accessible by consciousness [44]. This phenomenon plays a well-known role in glaucoma which often goes unnoticed by the patient. Thus, the fact that patients do not complain about deficits in peripheral motion perception might lead the practitioner not to examine this retinal region in detail. Yet, practical consequences have to be considered. If diminished sensitivity to motion raises the possibility that a patient’s transient attention might not be attracted to a moving stimulus, a behaviorally valuable eye movement may not be performed and a potentially hazardous situation may not be recognized.

Additionally, the tests available in routine clinical practice do not provide the appropriate stimuli to detect such defects. For instance, Holopigian et al. examined peripheral vision in patients with early ARM using standard electrophysiological and psychophysical tests (dark adaptation curves, electro-oculograms and electro-retinograms [23]. They found that only few subjects with early ARM developed disease-related effects in this region when examined with standard clinical tests.

Double-pulse resolution (DPR) and critical flicker fusion (CFF)

The results of DPR revealed distinct and statistically significant differences between the ARM group and age-matched controls up to 20° eccentricity. Furthermore, the increased foveal thresholds of double-pulse resolution in subjects with ARM parallel the elevated foveal CFF thresholds, which also show a dependency on age and a significant increase in subjects with ARM.

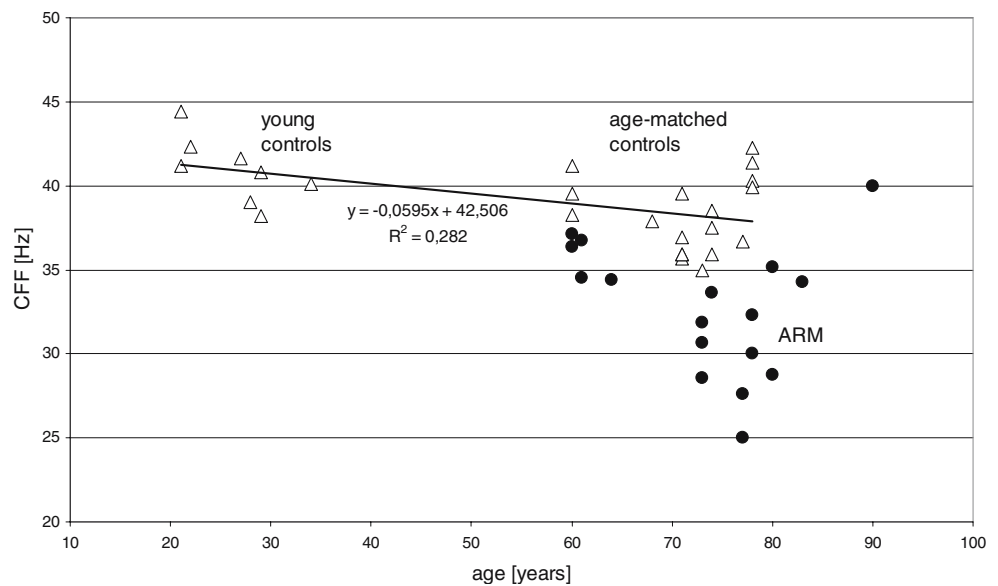
Comparison of the age-matched with the young control group shows an age dependency which confirms earlier

Table 3 Results of Mann-Whitney U-tests at each eccentricity for the ARM group and the age-matched control group; *U* is the statistical value of non-parametric Mann-Whitney test for comparison of

independent samples based on ordinal ranks; *z* is the estimated statistical value of normalized distribution of *U* values; *p* is the significance level

Eccentricity	Nasal field			Temporal field		
	<i>U</i>	<i>z</i>	<i>p</i>	<i>U</i>	<i>z</i>	<i>p</i>
5°	46.50	-2.55	0.011	46.50	-2.56	0.011
10°	45.00	-3.83	< 0.001	79.50	-2.78	0.005
20°	76.00	-2.89	0.003	61.00	-3.34	0.001

Fig. 7 Critical flicker fusion frequency as a function of age for the three groups. The regression line refers to the healthy controls



results [18, 46, 48, 61]. However, our results cannot be directly compared with the findings of Falsini et al. [13] who used a large homogeneous test field (18° diameter) that covered visual field regions with pronounced differences in functional characteristics.

The fact that reduced dynamic performance in our patients was found for two quite different methods of measurement emphasizes the presence of impaired temporal vision performance far beyond the macula and suggests a common underlying pathogenesis.

Color vision

The objective of the color vision test was to examine the relative involvement of the two neuronal subsystems of the primary visual pathway – magnocellular (M) and parvocellular (P) – in the previously obtained results. Both motion perception and temporal resolution are assumed to be predominantly conveyed by the M system, whereas color vision is predominantly mediated by the P system [31]. To simply find out whether color perception is intact, it is legitimate to use the color vision test foveally, or to allow the subjects to use the retinal area that serves them best. A (seemingly self-evident) conclusion that the deficits reported here may be caused by a specific damage to the M system can thus be rejected. Impaired color vision, as found here, shows that the P system is also affected.

The ARM group in our study showed a significantly lower foveal color vision performance than the age-matched control group. This would seem in conflict with the results of Frennesson et al. and Medina et al. who found no color vision deficits in subjects with ARM at an early stage [14, 42]. However, those studies used less sensitive tests with saturated colors, such as the Farnsworth D-15 test

or the Farnsworth-Munsell 100 Hue test, whereas our findings are based on the more sensitive Lanthony D-15 test which uses unsaturated colors [14, 42]. Since (static) contrast sensitivity was not measured here, we cannot estimate how strongly the color vision findings were influenced by the expectedly reduced contrast sensitivity of these patients.

Consequences

Even though the perceptual limitations measured in this study are not immediately evident to subjects with ARM, their relevance for daily life should not be underestimated. Their importance is due especially to the fact that segments of the near periphery assist safe mobility in general and driving a car in particular [21, 39]. Visual perception of moving stimuli has two functions of great importance in daily life. First, we perceive a stable, stationary world in which we are moving, despite the fact that nearly all image components on the retina are moving [43]. Being able to distinguish between the effects of self-motion and those of moving objects requires the detection and analysis of relative motion [47]. Second, our attention is constantly redirected to interesting and potentially dangerous objects, which typically cause a reorientation of gaze. These functions were examined previously in connection with the distinction between sustained and transient attention [3, 38, 44].

Because of the impairment of the central visual field in ARM, motion perception with peripheral vision is of even greater importance for these patients. Measurements with dynamic test stimuli are especially important for the assessment of driving ability of visually impaired persons [24]. Marron and Bailey examined contrast sensitivity and

visual acuity with regard to their importance for orientation and mobility [39]. Their results provide evidence that contrast sensitivity and the integrity of the visual field are of considerably greater importance for safe mobility than visual acuity. Studies from our own group show that dynamic peripheral sensitivity in a divided attention condition was the strongest predictor for safe driving in a group of healthy elderly drivers [53]. Recent studies have confirmed the importance of peripheral vision for driving by finding that contrast sensitivity and visual field limitations are the strongest predictors for mobility of visually impaired persons [10, 21, 35]. These studies demonstrate the importance of the assessment of visually guided performance regarding moving objects and contrast vision. In the tests at hand, these two tasks are linked. The growing possibilities for mobility of the elder generation with age-related visual impairment require examinations that take into account seniors' new lifestyles and can help ensure safe navigation.

Another relevant connection can be made with communication and the ability to read speech from the lips of a conversation partner, which is a difficulty faced by many elderly with additional hearing impairment. Although a general notion of the role of vision in speechreading has been established [56], the importance of motion sensitivity for speechreading has not been sufficiently investigated to date.

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