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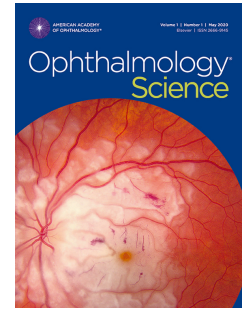
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Heterogenous visual function deficits in intermediate age-related macular degeneration – A MACUSTAR report

Hannah M.P. Dunbar, PhD, David P. Crabb, PhD, Charlotte Behning, MSc, Alison M. Binns, PhD, Amina Abdirahman, BSc, Jan H. Terheyden, MD, Stephen Poor MRCOphth, Robert P. Finger, MD Ph.D, Sergio Leal, MD, Adnan Tufail, MD, FRCOphth, Frank G. Holz, MD, Matthias Schmid, PhD, Ulrich F.O. Luhmann, PhD, On behalf of the MACUSTAR Consortium



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Heterogenous visual function deficits in intermediate age-related macular degeneration – A MACUSTAR report

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Running head

Visual function deficits in iAMD

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This article contains additional online-only material. The following should appear
online-only: Tables 4, 5 and 6

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Appendix:

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Abstract

Objective: To examine the extent to which visual function in Beckman age-related macular degeneration (AMD) disease stages differ from age similar peers with no AMD and using reference limits derived from those with no AMD, test the hypothesis that people with intermediate AMD (iAMD) have heterogenous visual function deficits.

Design: Cross-sectional analyses of a range of baseline visual function measures from the MACUSTAR study; an international, multi-center (n=20), non-interventional clinical trial.

Participants: 585 participants with iAMD (67% female, mean [standard deviation] age 72 [7] years) were recruited alongside 56 with no AMD (59% female, 68 [6]), 34 with early AMD (79% female, 72 [6]) and 43 with late AMD (49% female, 75 [6]).

Methods: Participants performed best-corrected visual acuity (BCVA), low luminance visual acuity (LLVA), Moorfields acuity test (MAT), Pelli-Robson contrast sensitivity (PR-CS), Small Print Standardized International Reading Speed Test (SPS), mesopic and scotopic Average Threshold (MesAT and ScoAT; Macular Integrity Assessment, iCare,) and Rod Intercept Time (RIT; AdaptDx, Lumithera).

Main Outcome Measures: Relationship between each visual function measure and disease classification was examined by linear regression adjusted for age, sex and phakic status. No AMD data were used to estimate normal reference limits for each

visual function test. iAMD scores were dichotomised against reference limits and proportion worse than each limit calculated.

Results: Relative to no AMD, SPS was significantly worse in early AMD ($p = 0.001$), all measures except SPS were significantly reduced in iAMD ($p < 0.02$) and all measures were markedly reduced in late AMD ($p < 0.0001$). 31% of iAMD participants breached reference limits for PR-CS, 29% for RIT, 24% for LLVA, 23% for MAT, 21% for BCVA, 20% for MesAT, 18% for ScoAT and 13% for SPS. 69.6% and 42.7% of iAMD participants breached ≥ 1 and ≥ 2 reference limits respectively, whereas 33.6% and 5.7% would be expected by chance.

Conclusions: A large proportion of people with structurally defined iAMD exhibit heterogenous visual function deficits outside normal reference limits. This observation may be relevant for the design and inclusion criteria of future interventional trials.

Trial registration:

Clinicaltrials.gov Reference: NCT03349801
<https://clinicaltrials.gov/ct2/show/NCT03349801>

Age-related macular degeneration (AMD) is a major cause of severe sight impairment globally affecting 196 million people, projected to rise to 288 million by 2040^[1]. The progressive stages of AMD, referred to as early, intermediate and late disease are identified based on structural features present in colour fundus photography^[2]. The value of incorporating optical coherence tomography (OCT) features within future classification paradigms is being explored^[3-5]. Despite relevance to patients, visual function measures are not currently considered within AMD classification systems and could potentially distinguish structurally similar disease with differing functional impacts, underlying pathology, or responsiveness to therapeutics.

Patient reported outcome studies suggest people with intermediate age-related macular degeneration (iAMD) experience difficulty under low luminance conditions^[6, 7]. Multiple measures of visual function under photopic, mesopic and scotopic conditions are also significantly worse in iAMD compared to healthy controls ^[8-15], however as absolute differences are small, clinical significance is unclear. Substantial functional heterogeneity within measures of low-luminance vision, contrast sensitivity, retinal sensitivity, and rod adaptation have been observed in iAMD ^[10, 12, 16] suggesting that comparing mean visual function measures between disease classifications may miss the presence of subgroups of people with iAMD experiencing meaningful functional impairment. Establishing evidence of visual function heterogeneity in people with iAMD, its prevalence and the extent to which different dimensions of visual function are affected could be useful for future trial design, regulatory purposes, and studies of new therapies.

Here we interrogate data from a large multi-center study on a range of clinical visual function assessments, to examine the extent to which visual function in AMD stages differs from age similar peers with no AMD and using reference limits derived from those with no AMD, test the hypothesis that people with iAMD have heterogenous visual deficits.

Methods:

MACUSTAR (Registration NCT03349801; www.clinicaltrials.gov) is a non-interventional 20 center clinical trial, the protocol of which has been published previously^[17]. Briefly, MACUSTAR has two parts; a cross-sectional study where structural and functional candidate endpoints have been evaluated with respect to their repeatability and ability to distinguish normal aging changes from Beckman^[2] classified AMD stages (No AMD, early AMD, iAMD and late AMD [includes both geographic atrophy and neovascular AMD])^[18, 19] and a longitudinal study where the ability of candidate endpoints to detect change over time and predict progression of iAMD to late AMD is being evaluated over a 3-year time course in a larger cohort with iAMD, with an extension to 6 year follow up recently announced. The present work uses the full baseline dataset across both components of the MACUSTAR study.

Written informed consent was obtained from all participants. The research was approved by individual local ethics committees (summarised in ^[20]) and conformed to the Declaration of Helsinki. Inclusion and exclusion criteria have previously been published^[17, 21]. Disease classification was confirmed by a central reading center based on multi-modal imaging (colour fundus photography, near-infrared reflectance

scanning laser ophthalmoscopy, fundus autofluorescence and spectral-domain optical coherence tomography) graded according to a standardized, predefined grading protocol based on Beckman AMD classification^[2, 22].

All participants performed a battery of visual function assessments including best-corrected visual acuity (BCVA), low luminance visual acuity (LLVA)^[23], Moorfields acuity test (MAT)^[24], Pelli-Robson contrast sensitivity (PR-CS)^[25], Small Print Standardized International Reading Speed Test (SPS)^[26, 27], average threshold from mesopic and scotopic fundus-controlled perimetry (MesAT and ScoAT; Macular Integrity Assessment, iCare, Finland) and rod intercept time (RIT) from dark adaptometry (AdaptDx, Lumithera, USA). A full description of all examination procedures including their standardized operating procedures (SOPs) have been published elsewhere^[18, 19]. As MACUSTAR was conceived to examine the potential of candidate endpoints within iAMD, test were selected with respect to relevance in iAMD, adequate measurement quality, compatibility with repeated standardized administration under multi center clinical trial conditions and being accepted by patients and examiners^[17]. All tests were performed monocularly with the study eye (defined as that with better BCVA or selected by the investigator if BCVA was equal in both eyes). Visual function data were subject to 6 monthly quality control procedures. MesAT, ScoAT and RIT data were assessed for quality and reliability as per their SOPs so that only high-quality data were retained for analysis. RIT values were capped at the maximum test duration (30 minutes). The relationship between each visual function measure and Beckman disease classification was plotted and examined by linear regression adjusted for age, sex and phakic status with Benjamini-Hochberg adjustment for multiple comparisons.

Cross-sectional data from those with no AMD were used to define a reference limit for normal function on each visual function test against which iAMD results were dichotomised. For visual function measures where higher values equate to better function, the reference limit was defined as the 5th percentile of baseline no AMD data. For measures where lower values equate to better function, the 95th percentile was used. Percentiles were computed using the default quantile type of the *quantile* function, which corresponds to continuous sample quantile type 7 described here^[28]. The proportion of participants with iAMD exhibiting function worse than each reference limit was calculated, together with the proportion falling outside, or breaching 0, 1, 2, 3, 4, 5, 6, 7 or 8 reference limits. Missing data points were classified as not exceeding the threshold. An UpSet plot^[29, 30] was used to graphically display the number and variety of reference limits breached. A negative binomial regression model was fitted to investigate the association between the number of breached visual function limits and phakic status. All analyses were performed in R, version 4.3.0^[31]. STROBE reporting guidelines were followed^[32].

Results:

Five hundred and eighty five participants with iAMD (67% female, mean [$\pm$ standard deviation] age 72 ± 7 years) were recruited alongside 56 with no AMD (59% female, 68 ± 6 years), 34 with early AMD (79% female, 72 ± 6 years) and 43 with late AMD (49% female, 75 ± 6 years). More than 99% of participants completed BCVA, LLVA, MAT and PR-CS measures, with 93.7% performing the SPS. SPS was not performed at one site (n=30) where a native language (Danish) test was not available. The proportion of participants able to return a valid MesAT, ScoAT and

RIT measurement was 90.8%, 85.2% and 69.1% respectively. Table 1 provides the distribution of demographic and visual function measures by disease classification, presented graphically in figure 1.

A linear regression model adjusted for age, sex and phakic status examined the relationship between each visual function measure and disease classification, where no AMD was the reference level. Model results are summarised in Table 2. Relative to no AMD, only SPS was significantly worse on average in early AMD ($p=0.001$), whereas all measures apart from SPS were significantly worse in iAMD ($p<0.02$). Though statistically significant, in each case model estimates were smaller than the limits of agreement defined during the cross-sectional part of MACUSTAR.^[18, 19] All visual function measures were significantly and markedly poorer in late AMD relative to no AMD ($p<0.0001$), with all estimates being between 1.6x to 5x larger than the limits of agreement defined on the MACUSTAR late AMD cohort.^[18, 19] Additionally age was associated with all visual function measures except for RIT ($p<0.0003$).

Calculated reference limits and the proportion of iAMD participants breaching said limits for each visual function test is provided in Table 3 and shown in Figure 1 as a red dashed line. The proportion of those with iAMD breaching individual reference limits was largest for PR-CS (31.3%), followed by RIT (29.4%), LLVA, (24.1%) and MAT (23.2%). Roughly one fifth breached BCVA (20.5%), MesAT (19.8%) and ScoAT (17.9%) reference limits, dropping to an eighth for SPS (12.6%). Average differences between each impaired subgroup and the no AMD group were calculated and are shown in Table 3. The impaired subgroup for BCVA, LLVA and MAT were between 0.22 LogMAR (11 letters) - 0.32 LogMAR (16 letters) poorer than the no

AMD group. PR-CS was 0.35 LogCS (7 letters) poorer, SPS reading speed was 82 wpm slower, MesAT and ScoAT were 7.2dB and 8.4dB lower respectively and RIT was 7.89 minutes slower.

407 (69.6%) iAMD participants breached the no AMD reference limits on at least one visual function test, with 250 (42.7%) breaching at least 2. Binomial probability calculations were used to determine how many participants would be expected to exceed at least one ($[1 - 1 \cdot (1-0.05)^8] = 33.6\%$) and at least 2 ($[1 - 1 \cdot (1-0.05)^8 - 8! / 7! \cdot 0.05 \cdot (1-0.05)^7] = 5.7\%$) limit by chance under the null hypothesis that people exhibiting function worse than the reference limit have equivalent visual function to peers with no AMD. The number and proportion of those with iAMD who breached 0 – 8 reference limits are provided in Table 4 (available at <https://www.aaojournal.org>).

The Upset plot in Figure 2 graphically displays the quantity of iAMD participants who breached the reference limit for each visual function test and the extent to which iAMD participants breached reference limits on single and / or multiple visual function tests. Though the PR-CS reference limit was breached most commonly overall, RIT was the most common reference limit breached in isolation, whereas individuals who breached the PR-CS limits, more often breached one or more additional limit in combination. The most common combination of 2 reference limits breached was PR-CS and MAT ($n = 134$, [22.9%]), with RIT and SPS being the least common ($n = 47$, [8.0%]). Four individuals exceeded all 8 limits. No association was found between the number of breached visual function limits and phakic status ($p > 0.16$).

Since reference limits calculated for these analyses account for measurement variability between those with no AMD but not within individuals, a sensitivity analysis was performed exploiting no AMD data obtained at both baseline (Day 0) and validation (Day 14 ± 7) study visits. Results are provided in Table 5 and 6 (available at <https://www.aaojournal.org>). Applying secondary reference limits revealed 360 (61.5%) iAMD participants breached at least one limit and 209 (35.7%) breached at least 2.

Discussion

In this large, multi-center dataset, a range of visual function tests did not show clinically meaningful average differences in functional performance between normal aging and both early AMD and iAMD. Conversely visual function in those with late AMD was markedly and significantly reduced, exceeding limits of agreement defined for the MACUSTAR visual function test battery by between 1.6 and 5 times. Despite average visual function in iAMD being clinically comparable to no AMD on a population level, 69.6% of iAMD participants had deficits in at least 1 visual function test falling outside reference limits established in visually healthy peers; more than two-fold greater than that expected by chance. Additionally, 42.7% of participants with iAMD had deficits in two or more visual function tests; seven times more than that expected by chance. Estimates of the proportion affected by chance assume tests are unrelated. Correlation coefficients between the visual function measures in this cohort are in the weak to moderate range (Under review with Ophthalmologica: Terheyden, 2024: The Heterogeneous Spectrum of Functional, Structural and Patient-Reported Outcomes in Intermediate Age-Related Macular Degeneration – A MACUSTAR Study Report). Taken together, this supports the notion that functional

heterogeneity in the baseline iAMD population of MACUSTAR cannot be explained as a chance finding. That said, the observed proportions depend on the veracity of the reference limits used.

There are no universally accepted thresholds for normal function in older eyes. Therefore, we defined reference limits on data from 56 visually healthy peers in the same study. This dataset has the unique advantage of being obtained under the same multi-center, multi-technician conditions, using the same publicly available SOPs^[18, 19]. We additionally exploited the availability of repeat no AMD visual function data to assess the impact of intra-observer variability on our calculated reference limits. This sensitivity analysis adopted the cautious approach of basing a set of secondary reference limits on the worst of 2 visual function measurements. Comparing these to our initial limits showed that for letter scored tests (BCVA, LLVA, MAT and PR-CS) reference limits differed by between 0 and 1.5 letters. SPS limits differed by 3 wpm, microperimetry average threshold measures by between 0.8 – 1dB and RIT by 0.27 minutes. Logically, applying these adjusted thresholds resulted in a smaller proportion of iAMD participants outside reference limits, however the proportion outside at least one (61.5%) and 2 (35.7%) limits were roughly 1.8x and 6x that expected by chance respectively, corroborating our primary finding that a large proportion of participants with iAMD have deficits in visual function falling outside reference limits established in visually healthy peers.

A comparative study of visual function in normal controls and iAMD assessed BCVA, LLVA, MAT, PR-CS, SPS, MesAT and ScoAT in 24 control eyes in a single center (61.7 ± 6.1 years) using equivalent equipment and testing protocols.^[9] Using their published no AMD data to calculate the mean ± 2 x standard deviation for each

visual function measure as a proxy for the 5th/95th percentile revealed roughly equivalent values to our reference limits (BCVA: 0.12 LogMAR; LLVA: 0.38 LogMAR; MAT: 0.50 LogMAR; PR-CS: 1.50 LogCS; SPS: 116wpm; MesAT: 22.7dB; ScoAT: 19.5dB). The single center ALSTAR2 study has also assessed a range of visual function parameters in 239 people (70.8 ± 5.6 years) in normal macular health (Age-Related Eye Disease Study^[33] [AREDS] grade 1).^[13, 34] Though defining reference limits was not the primary aim of ALSTAR2, as one of the largest published studies of normal macular health it serves as a very useful comparator. Further there is some overlap between the visual function test batteries of ALSTAR2 and MACUSTAR (both assess BCVA, LLVA, contrast sensitivity, MesAT, ScoAT and RIT), though testing equipment and protocols differ. These factors limit a true, direct comparison. Nevertheless, proxy reference limits calculated using baseline ALSTAR2 control data (using the method described above) reveal slightly more conservative values than our reference limits for all tests except RIT (BCVA: 0.15 LogMAR; LLVA: 0.42 LogMAR; MARS contrast sensitivity^[35]: 1.39 LogCS; MesAT: 19.1dB; ScoAT: 16.0dB). A direct comparison for RIT is more challenging as test parameters differ. Based on data from the same 12° retinal location used in MACUSTAR, though using a higher bleach and longer maximum test duration^[34], the proxy RIT limit is 16.2mins. Recent evidence suggests dark adaptation deficits in early AMD are likely greatest when assessed at 5° eccentricity^[34]. In MACUSTAR, the 12° test location was chosen based on pilot data showing that a deficit is present in people with iAMD at 12°, and that a smaller proportion of participants would demonstrate a ceiling effect within a clinically practical test duration.^[36-38] In line with this pilot data, our results support the existence of an RIT deficit at 12°, as a higher proportion of participants fell outside the RIT reference limit than any other functional

parameter except for PR-CS. However, we note that a more centrally located target may have identified an even higher proportion of individuals with abnormal RIT, had the test duration been extended to 45 or 60 minutes. In addition to test parameter differences and the different method of reference limit calculation, the slightly older age of the ALSTAR2 cohort ($[70.8 \pm 5.6]$ versus $[68 \pm 6]$ years) may also contribute to the difference in reference limits between studies.

MACUSTAR reference limits presented here cannot be considered true normative cut off values given the small dataset on which they are based; this is a limitation. Nevertheless, we suggest this method of defining reference limits for exposing functional heterogeneity is justified by its statistical underpinning, consensus with previous work and cautious nature. However, future work characterizing normative visual function on the MACUSTAR test battery in a larger cohort with a wider and balanced age-range is warranted to fully explore the concept of functional heterogeneity in iAMD and other ocular disease cohorts.

Functional heterogeneity in AREDS defined iAMD has been previously observed based on mesopic microperimetry, low luminance deficit and dark adaptation measures in single center studies.^[36, 38, 39] Here we add further evidence that this heterogeneity extends to a wider range of clinical visual function tests and is observable in a large, multi-center population of people with Beckman classified iAMD examined under clinical trial conditions. Recent work using qualitative autofluorescence to assess early changes in AMD suggests some eyes classified as Beckman iAMD may be at an earlier stage disease stage^[40]. This suggests functional heterogeneity may not only be the preserve of iAMD but may extent to those with earlier disease.

Though a certain degree of heterogeneity could be introduced by technical variability or execution, especially in a multi center setting, efforts were employed to minimise this. Technician were certified, 6 monthly quality control assessments were performed to recognise any additional training needs and to identify and exclude invalid data, test-retest variability was determined for all tests^[18, 19] and pilot testing performed to optimise test parameters^[37, 41]. Thus, we consider our data to have high quality and conclusions valid.

The average differences between the iAMD subgroup with impaired function and normal peers exceed the test-retest limits for each visual function test^[18, 19], supporting the clinical relevance of functional heterogeneity in iAMD. Furthermore, differences approximate changes proposed to represent clinical relevance (15-letters on acuity tests^[42], 6-letters on PR-CS^[43, 44], 80 wpm on SPS^[45, 46], 7dB in retinal sensitivity^[47], and 6.5 minutes on RIT albeit at a different retinal location^[48]) based on methods including expert consensus, association of functional measures with task performance or self-report and diagnostic sensitivity and specificity.

Deficits were most commonly found in PR-CS and RIT, however PR-CS deficits occurred more often in combination with other deficits whilst RIT deficits were more frequently seen in isolation suggesting the possibility of distinct functional profiles within the structural classification of iAMD. For example, given delayed RIT in normal macular health is associated with development of incident AMD after 3 years,^[49] those with RIT deficits may be at an earlier stage of progression than those who have accumulated multiple visual function deficits. It is also accepted that functional performance in iAMD varies with and without reticular pseudodrusen

(RPD)^[34, 50-54]. As such, differing functional outcomes may be associated with distinct structural phenotypes.

Given the functional impact of cataract, we were reassured phakic status was not related to the number breached visual function limits. Age however was associated with all visual function measures apart from RIT. If age deputises for disease duration, functional heterogeneity may in part be explained by various stages of progression within the baseline iAMD cohort, rather than visual deficits indicating faster progression toward late disease. That said, 549/585 (94%) of the iAMD cohort had bilateral iAMD, with the remainder having iAMD in the study eye and late AMD in the fellow eye 46/585 (8%). With late AMD in the fellow eye associated with higher rates of progression to late disease^[55], symmetrical disease in the vast majority of the iAMD population may reduce the likelihood that the heterogeneity observed is the result of differing stages of progression. We acknowledge that chronological, not biological age was adjusted for. It has been shown that those with a higher biological than chronological age are at higher risk of poorer health outcomes, which may be influencing the heterogeneity observed^[56]. We will shortly investigate whether iAMD associated with functional deficits increases the risk of progression to late AMD with longitudinal MACUSTAR data. If so, this may go toward supporting the clinical relevance of functional impairment in iAMD and its potential to be a treatment indication in itself.

Functional heterogeneity may also have a substantial bearing on inclusion criteria for future interventional trials. If criteria are based solely on structural classification, this risks recruiting a cohort with an assorted or variable profile of visual function deficits.

If, as regulators prefer, visual function endpoints are employed, baseline variation within the assessed visual domain may obscure any potential intervention related signal.

There are further limitations in this work that should be considered. As described above, the calculation of reference limits is based on a limited sample of 56 no AMD participants. Furthermore, the small size of the early ($n = 34$) and late AMD ($n = 43$) groups are also a limitation. The rationale for our sample sizes has been explained previously^[18]. That visual function tests were not chosen based on AMD pathogenesis could be considered a limitation, however this was not customary at the time of study design. Rather as described in the methods section, clinical data informed test selection with an emphasis on tests that could potentially be adopted in multi center clinical trial settings.

We conclude that when multiple domains of visual function in normal aging are compared to early AMD and iAMD on population level, average differences across groups are not clinically meaningful, being considerably less than limits of agreement. However, population level change may obscure person level functional decline in iAMD. Using reference limits established in visually healthy peers, 69.6% of those with structurally defined iAMD have at least one functional deficit, more than two fold that expected by chance. 42.7% have at least two deficits, seven times greater than chance. Average differences between those with iAMD who display functional impairment and those with no AMD approximate clinically meaningful change across visual function assessments. This evidence of visual function heterogeneity in iAMD in our large, multi-center cohort may be relevant to the design and participant inclusion criteria of future intervention iAMD trials, especially those

aiming to halt or slow photoreceptor degeneration and loss. It remains to be seen whether people with iAMD who have specific visual function deficits are more likely to progress to late AMD, or whether these findings are a reflection of various stages of progression within the MACUSTAR iAMD cohort.

Tables titles, descriptions and footnotes

Table 1: Summary of demographic and visual function measures.

Summary of demographic and visual function measures segregated by Beckman disease classification.

*AMD: age-related macular degeneration; SD: standard deviation; Min: minimum; Max: maximum; LogMAR: logarithm of the minimum angle of resolution; LogCS: logarithm of contrast sensitivity; ~20/XX approximate Snellen equivalent; wpm: words per minute; IReST: International Reading Speed Test; dB: decibels. *30 participants without access to Danish language IReST included in missing data rate.*

Table 2: Relationship between visual function measures and disease classification

Linear regression model examining the relationship between each visual function measure (as dependent variable) and disease classification, adjusted for age, sex and phakic status.

522

523 *AMD: age-related macular degeneration; i: intermediate; BCVA: best corrected*
 524 *visual acuity; LLVA: low luminance visual acuity; MAT: Moorfields acuity test; PR-*
 525 *CS: Pelli-Robson contrast sensitivity; SPS: Small print standardised International*
 526 *Reading Speed Test; MesAT: Mesopic average threshold; ScoAT: Scotopic average*
 527 *threshold; RIT: Rod Intercept Time; LogMAR: logarithm of the minimum angle of*
 528 *resolution; LogCS: logarithm of contrast sensitivity; wpm: words per minute; dB:*
 529 *decibel, mins: minutes. Bold indicates significant result.*

530

531 **Table 3: Summary of iAMD participants breaching visual function reference**
 532 **limits**

533

534 Number and proportion iAMD participants breaching the reference limit for each
 535 visual function test calculated as a proportion of the complete iAMD cohort (585).
 536 Mean $\pm$ standard deviation of those breaching the reference limited (functionally
 537 impaired) and not breaching the reference limit (function not impaired) for each
 538 variable. No AMD data provided for comparison between iAMD function impaired
 539 and no AMD.

540

541 *BCVA: best corrected visual acuity; LLVA: low luminance visual acuity; MAT:*
 542 *Moorfields acuity test; PR-CS: Pelli-Robson contrast sensitivity; SPS: Small Print*
 543 *Standardised International Reading Speed Test; MesAT: Mesopic average*
 544 *threshold; ScoAT: Scotopic average threshold; RIT: Rod Intercept Time; LogMAR:*
 545 *logarithm of the minimum angle of resolution; LogCS: logarithm of contrast*
 546 *sensitivity; wpm: words per minute; dB: decibel, mins: minutes.*

Table 4: Summary of iAMD participants breaching 0 – 8 reference limits

Number and proportion of iAMD participants breaching 0 through 8 worse than reference limits.

AMD: age-related macular degeneration; i: intermediate.

Table 5: Summary of secondary reference limits and proportion of iAMD participants breaching secondary reference limits.

Number and proportion iAMD participants breaching secondary worse than reference limits for each visual function test calculated as a proportion of the complete iAMD cohort (585).

BCVA: best corrected visual acuity; LLVA: low luminance visual acuity; MAT: Moorfields acuity test; PR-CS: Pelli-Robson contrast sensitivity; SPS: Small Print Standardised International Reading Speed Test; MesAT: Mesopic average threshold; ScoAT: Scotopic average threshold; RIT: Rod Intercept Time; LogMAR: logarithm of the minimum angle of resolution; LogCS: logarithm of contrast sensitivity; wpm: words per minute; dB: decibel, mins: minutes.

Table 6: Summary of iAMD participants breaching 0 – 8 secondary reference limits

Number and proportion iAMD participants breaching 0 through 8 secondary worse than reference limits.

AMD: age-related macular degeneration; i: intermediate.

Figures Legends

Figure 1: Distribution of the visual function measures by disease classification.

Red dashed line indicates reference limit for each test based on no AMD data. AMD: age-related macular degeneration; i: intermediate; BCVA: best corrected visual acuity; LLVA: low luminance visual acuity; MAT: Moorfields acuity test; PR-CS: Pelli-Robson contrast sensitivity; SPS: Small print standardised International Reading Speed Test; MesAT: Mesopic average threshold; ScoAT: Scotopic average threshold; RIT: Rod Intercept Time; LogMAR: logarithm of the minimum angle of resolution; LogCS: logarithm of contrast sensitivity; wpm: words per minute; dB: decibel, mins: minutes.

Figure 2: Upset plot describing number and extent of reference limits breached in participants with iAMD.

Horizontal black bars indicate the set size or number of iAMD participants who breached the reference limit for each visual function (VF) test shown by the adjacent

label. Vertical black bars indicate the intersection size or number of iAMD participants who breached the reference limit of the visual function test(s) indicated by the filled black circles beneath. For example, the left most vertical black bar indicates that 59 iAMD participants breached the RIT reference limit only, whilst the right most vertical black bar indicates that 4 iAMD participants breached the reference limit on all 8 visual function tests. BCVA: best corrected visual acuity; LLVA: low luminance visual acuity; MAT: Moorfields acuity test; PR-CS: Pelli-Robson contrast sensitivity; SPS: Small Print Standardised International Reading Speed Test; MesAT: Mesopic average threshold; ScoAT: Scotopic average threshold; RIT: Rod Intercept Time.

References

1. Wong, W.L., et al., *Global prevalence of age-related macular degeneration and disease burden projection for 2020 and 2040: a systematic review and meta-analysis*. The Lancet Global Health, 2014. 2(2): p. e106-e116.
2. Ferris III, F.L., et al., *Clinical classification of age-related macular degeneration*. Ophthalmology, 2013. 120(4): p. 844-851.
3. Guymer, R.H., et al., *Incomplete Retinal Pigment Epithelial and Outer Retinal Atrophy in Age-Related Macular Degeneration: Classification of Atrophy Meeting Report 4*. Ophthalmology, 2020. 127(3): p. 394-409.
4. Jaffe, G.J., et al., *Imaging Features Associated with Progression to Geographic Atrophy in Age-Related Macular Degeneration: Classification of Atrophy Meeting Report 5*. Ophthalmology Retina, 2021. 5(9): p. 855-867.
5. Wu, Z., et al., *OCT Signs of Early Atrophy in Age-Related Macular Degeneration: Interreader Agreement: Classification of Atrophy Meetings Report 6*. Ophthalmology Retina, 2022. 6(1): p. 4-14.
6. McGuinness, M.B., et al., *Relationship Between Rod-Mediated Sensitivity, Low-Luminance Visual Acuity, and Night Vision Questionnaire in Age-Related Macular Degeneration*. Translational Vision Science & Technology, 2020. 9(6): p. 30.
7. Thompson, A.C., et al., *Association of Low Luminance Questionnaire With Objective Functional Measures in Early and Intermediate Age-Related Macular Degeneration*. Investigative Ophthalmology & Visual Science, 2018. 59(1): p. 289-297.
8. Pondorfer, S.G., et al., *Association of Visual Function Measures with Drusen Volume in Early Stages of Age-Related Macular Degeneration*. Investigative Ophthalmology & Visual Science, 2020. 61(3): p. 55.
9. Pondorfer, S.G., et al., *Detecting vision loss in intermediate age-related macular degeneration: A comparison of visual function tests*. PLoS ONE [Electronic Resource], 2020. 15(4): p. e0231748.

10. Cocce, K.J., et al., *Visual Function Metrics in Early and Intermediate Dry Age-related Macular Degeneration for Use as Clinical Trial Endpoints*. American Journal of Ophthalmology, 2018. **189**: p. 127-138.
11. Chandramohan, A., et al., *Visual Function Measures in Early and Intermediate Age-Related Macular Degeneration*. Retina, 2016. **36**(5): p. 1021-31.
12. Wu, Z., et al., *Low-luminance visual acuity and microperimetry in age-related macular degeneration*. Ophthalmology, 2014. **121**(8): p. 1612-9.
13. Owsley, C., et al., *How Vision Is Impaired From Aging to Early and Intermediate Age-Related Macular Degeneration: Insights From ALSTAR2 Baseline*. Translational Vision Science & Technology, 2022. **11**(7)(17).
14. Vujosevic, S., et al., *Detection of macular function changes in early (AREDS 2) and intermediate (AREDS 3) age-related macular degeneration*. Ophthalmologica, 2011. **225**(3): p. 155-160.
15. Guymer, R.H., R.S. Tan, and C.D. Luu, *Comparison of Visual Function Tests in Intermediate Age-Related Macular Degeneration*. Translational Vision Science & Technology, 2021. **10**(12): p. 14.
16. Csaky, K.G., *Cross-Sectional Study of Cone Function in Age-Related Macular Degeneration Subjects With Non-foveal Nascent Geographic Atrophy*. American Journal of Ophthalmology, 2023. **247**: p. 25-34.
17. Finger, R.P., et al., *MACUSTAR: Development and Clinical Validation of Functional, Structural, and Patient-Reported Endpoints in Intermediate Age-Related Macular Degeneration*. Ophthalmologica, 2019. **241**(2): p. 61-72.
18. Dunbar, H.M., et al., *Repeatability and Discriminatory Power of Chart-Based Visual Function Tests in Individuals With Age-Related Macular Degeneration: A MACUSTAR Study Report*. JAMA ophthalmology, 2022.
19. Higgins, B.E., et al., *Test-Retest Variability and Discriminatory Power of Measurements From Microperimetry and Dark Adaptation Assessment in People With Intermediate Age-Related Macular Degeneration—A MACUSTAR Study Report*. Translational Vision Science & Technology, 2023. **12**(7): p. 19-19.
20. Terheyden, J.H., et al., *Challenges, facilitators and barriers to screening study participants in early disease stages-experience from the MACUSTAR study*. BMC Medical Research Methodology, 2021. **21**(1): p. 1-8.
21. Terheyden, J.H., et al., *Clinical study protocol for a low-interventional study in intermediate age-related macular degeneration developing novel clinical endpoints for interventional clinical trials with a regulatory and patient access intention-MACUSTAR*. Trials [Electronic Resource], 2020. **21**(1): p. 659.
22. Saßmannshausen, M., et al., *Intersession Repeatability of Structural Biomarkers in Early and Intermediate Age-Related Macular Degeneration: A MACUSTAR Study Report*. Translational Vision Science & Technology, 2022. **11**(3): p. 27-27.
23. Sunness, J.S., et al., *Low luminance visual dysfunction as a predictor of subsequent visual acuity loss from geographic atrophy in age-related macular degeneration*. Ophthalmology, 2008. **115**(9): p. 1480-1488. e2.
24. Shah, N., et al., *Visual acuity loss in patients with age-related macular degeneration measured using a novel high-pass letter chart*. British Journal of Ophthalmology, 2016. **100**(10): p. 1346-52.
25. Pelli, D. and J. Robson. *The design of a new letter chart for measuring contrast sensitivity*. in *Clinical Vision Sciences*. 1988. Citeseer.
26. Hahn, G.A., et al., *New standardised texts for assessing reading performance in four European languages*. British Journal of Ophthalmology, 2006. **90**(4): p. 480-4.

27. Trauzettel-Klosinski, S., K. Dietz, and I.R.S. Group, *Standardized assessment of reading performance: the New International Reading Speed Texts IReST*. Investigative Ophthalmology & Visual Science, 2012. **53**(9): p. 5452-61.
28. Hyndman, R.J. and Y. Fan, *Sample quantiles in statistical packages*. The American Statistician, 1996. **50**(4): p. 361-365.
29. Lex, A., et al., *UpSet: visualization of intersecting sets*. IEEE transactions on visualization and computer graphics, 2014. **20**(12): p. 1983-1992.
30. Conway, J.R., A. Lex, and N. Gehlenborg, *UpSetR: an R package for the visualization of intersecting sets and their properties*. Bioinformatics, 2017. **33**(18): p. 2938-2940.
31. R Development Core Team. *A language and environment for statistical computing*. <http://www.R-project.org> 2009.
32. Vandenbroucke, J.P., et al., *Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): explanation and elaboration*. Annals of internal medicine, 2007. **147**(8): p. W-163-W-194.
33. Davis, M.D., et al., *The Age-Related Eye Disease Study severity scale for age-related macular degeneration: AREDS report No. 17*. Archives of ophthalmology (Chicago, Ill.: 1960), 2005. **123**(11): p. 1484-1498.
34. Owsley, C., et al., *Biologically Guided Optimization of Test Target Location for Rod-mediated Dark Adaptation in Age-related Macular Degeneration: Alabama Study on Early Age-related Macular Degeneration 2 Baseline*. Ophthalmology Science, 2023. **3**(2): p. 100274.
35. Arditi, A., *Improving the design of the letter contrast sensitivity test*. Investigative Ophthalmology & Visual Science, 2005. **46**(6): p. 2225-9.
36. Owsley, C., M.E. Clark, and G. McGwin, Jr., *Natural History of Rod-Mediated Dark Adaptation over 2 Years in Intermediate Age-Related Macular Degeneration*. Translational Vision Science & Technology, 2017. **6**(3): p. 15.
37. Binns, A.M., et al., *Determining Optimal Test Parameters for Assessing Dark Adaptation in People With Intermediate Age-Related Macular Degeneration*. Investigative Ophthalmology & Visual Science, 2018. **59**(4): p. AMD114-AMD121.
38. Nguyen, C.T., et al., *Longitudinal changes in retinotopic rod function in intermediate age-related macular degeneration*. Investigative ophthalmology & visual science, 2018. **59**(4): p. AMD19-AMD24.
39. Hsu, S.T., et al., *Longitudinal Study of Visual Function in Dry Age-Related Macular Degeneration at 12 Months*. Ophthalmology Retina, 2019. **3**(8): p. 637-648.
40. Berlin, A., et al., *Quantitative autofluorescence at AMD's beginnings highlights retinal topography and grading system differences: ALSTAR2 baseline*. Ophthalmologica. Journal International d'ophtalmologie. International Journal of ophthalmology. Zeitschrift fur Augenheilkunde, 2024.
41. Welker, S.G., et al., *Retest Reliability of Mesopic and Dark-Adapted Microperimetry in Patients With Intermediate Age-Related Macular Degeneration and Age-Matched Controls*. Investigative Ophthalmology & Visual Science, 2018. **59**(4): p. AMD152-AMD159.
42. Csaky, K.G., E.A. Richman, and F.L. Ferris, *Report from the NEI/FDA ophthalmic clinical trial design and endpoints symposium*. Investigative ophthalmology & visual science, 2008. **49**(2): p. 479-489.
43. West, S.K., et al., *How does visual impairment affect performance on tasks of everyday life?: The SEE Project*. Archives of Ophthalmology, 2002. **120**(6): p. 774-780.

44. Rubin, G.S., et al., *The association of multiple visual impairments with self-reported visual disability: SEE project*. Investigative ophthalmology & visual science, 2001. **42**(1): p. 64-72.
45. Carver, R.P., *Reading rate: Theory, research, and practical implications*. Journal of Reading, 1992. **36**(2): p. 84-95.
46. Rubin, G.S., *Measuring reading performance*. Vision Research, 2013. **90**: p. 43-51.
47. Weinreb, R.N. and P.L. Kaufman, *Glaucoma research community and FDA look to the future, II: NEI/FDA Glaucoma Clinical Trial Design and Endpoints Symposium: measures of structural change and visual function*. Investigative ophthalmology & visual science, 2011. **52**(11): p. 7842-7851.
48. Jackson, G.R., et al., *Diagnostic sensitivity and specificity of dark adaptometry for detection of age-related macular degeneration*. Investigative Ophthalmology & Visual Science, 2014. **55**(3): p. 1427-31.
49. Owsley, C., et al., *Visual Function in Older Eyes in Normal Macular Health: Association with Incident Early Age-Related Macular Degeneration 3 Years Later*. Investigative Ophthalmology & Visual Science, 2016. **57**(4): p. 1782-9.
50. Grewal, M.K., et al., *Functional clinical endpoints and their correlations in eyes with AMD with and without subretinal drusenoid deposits-a pilot study*. Eye, 2022. **36**(2): p. 398-406.
51. Kumar, H., et al., *Exploring Reticular Pseudodrusen Extent and Impact on Mesopic Visual Sensitivity in Intermediate Age-Related Macular Degeneration*. Investigative Ophthalmology & Visual Science, 2022. **63**(6): p. 14.
52. Zhang, Y., et al., *Spatial Dissociation of Subretinal Drusenoid Deposits and Impaired Scotopic and Mesopic Sensitivity in AMD*. Investigative Ophthalmology & Visual Science, 2022. **63**(2): p. 32.
53. Flamendorf, J., et al., *Impairments in Dark Adaptation Are Associated with Age-Related Macular Degeneration Severity and Reticular Pseudodrusen*. Ophthalmology, 2015. **122**(10): p. 2053-62.
54. Lad, E.M., et al., *Longitudinal evaluation of visual function impairments in early and intermediate age-related macular degeneration patients*. Ophthalmology Science, 2022: p. 100173.
55. Chakravarthy, U., et al., *Progression from early/intermediate to advanced forms of age-related macular degeneration in a large UK cohort: rates and risk factors*. Ophthalmology Retina, 2020. **4**(7): p. 662-672.
56. Liu, W.S., et al., *Association of biological age with health outcomes and its modifiable factors*. Aging Cell, 2023. **22**(12): p. e13995.

		No AMD (n = 56)	Early AMD (n = 34)	Intermediate AMD (n = 585)	Late AMD (n = 43)
Age, years	Mean (SD)	68 (6)	72 (6)	72 (7)	75 (6)
	Median [Min, Max]	68 [55, 88]	72 [57, 82]	72 [55, 88]	75 [64, 84]
Sex	Female	33 (58.9%)	27 (79.4%)	389 (67%)	21 (48.8%)
	Male	23 (41.1%)	7 (20.6%)	196 (33%)	22 (51.2%)
Best Corrected Visual Acuity (BCVA), LogMAR	Mean (SD)	-0.04 (~20/20) (0.08)	0.01 (~20/20) (0.08)	0.03 (~20/20) (0.10)	0.77 (~20/125) (0.25)
	Median [Min, Max]	-0.06 (~20/16) [-0.24, 0.14]	0.02 (~20/20) [-0.18, 0.20]	0.02 (~20/20) [-0.24, 0.28]	0.84 (~20/125) [0.20, 1.24]
	Missing	0	0	1 (0.2%)	0
Low Luminance Visual Acuity (LLVA), LogMAR	Mean (SD)	0.14 (~20/25) (0.09)	0.19 (~20/32) (0.14)	0.24 (~20/32) (0.16)	0.95 (~20/200) (0.24)
	Median [Min, Max]	0.13 (~20/25) [-0.02, 0.38]	0.17 (~20/32) [-0.04, 0.50]	0.22 (~20/32) [-0.14, 1.08]	0.96 (~20/200) [0.52, 1.52]
	Missing	0	0	2 (0.3%)	0
Moorfields Acuity Test (MAT), LogMAR	Mean (SD)	0.36 (~20/50) (0.11)	0.42 (~20/50) (0.12)	0.44 (~20/50) (0.16)	1.03 (~20/200) (0.20)
	Median [Min, Max]	0.35 (~20/50) [0.16, 0.62]	0.41 (~20/50) [0.20, 0.72]	0.42 (~20/50) [-0.10, 1.10]	1.00 (~20/200) [0.66, 1.48]
	Missing	0	0	1 (0.2%)	0
Pelli Robson Contrast Sensitivity (PR-CS), LogCS	Mean (SD)	1.71 (0.16)	1.63 (0.16)	1.55 (0.18)	1.07 (0.34)
	Median [Min, Max]	1.75 [1.05, 1.95]	1.65 [1.25, 1.90]	1.55 [0.75, 1.95]	1.15 [0.20, 1.55]
	Missing	0	0	2 (0.3%)	0
Small Print Standardised (SPS) IReST, wpm	Mean (SD)	156 (38)	123 (44)	144 (40)	25(36)
	Median [Min, Max]	154 [77, 293]	129 [51, 215]	147 [0, 285]	1 [0, 132]
	Missing*	1 (1.8%)	0 (0%)	37 (6.3%)	4 (9.3%)
Mesopic Average Threshold (MesAT), dB	Mean (SD)	25.4 (2.06)	23.9 (2.61)	23.3 (3.65)	7.92 (6.85)
	Median [Min, Max]	25.6 [19.4, 29.2]	24.6 [17.1, 27.6]	24.2 [0.50, 29.4]	7.20 [0, 21.1]
	Missing	2 (3.6%)	0 (0%)	58 (9.9%)	6 (14.0%)
Scotopic Average Threshold (ScoAT), dB	Mean (SD)	21.30 (2.44)	19.60 (3.27)	18.70 (3.78)	6.0 (6.0)
	Median [Min, Max]	21.5 [16.1, 29.2]	20.3 [12.4, 24.2]	19.6 [0.20, 25.6]	3.20 [0, 20.6]
	Missing	3 (5.4%)	0 (0%)	89 (15.2%)	14 (32.6%)
Rod Intercept Time, (RIT) at 12° inferiorly, minutes	Mean (SD)	4.24 (1.36)	6.15 (4.81)	7.21 (5.07)	13.4 (11.8)
	Median [Min, Max]	4.20 [1.58, 9.02]	5.21 [2.68, 30.0]	5.62 [1.59, 30.0]	7.25 [1.87, 30.0]
	Missing	13 [23.2%]	5 (14.7%)	177 (30.3%)	27 (62.8%)

Table 1: Summary of demographic and visual function measures.

Summary of demographic and visual function measures segregated by Beckman disease classification.

AMD: age-related macular degeneration; SD: standard deviation; Min: minimum; Max: maximum; LogMAR: logarithm of the minimum angle of resolution; LogCS: logarithm of contrast sensitivity; ~20/XX approximate Snellen equivalent; wpm: words per minute; IReST: International Reading Speed Test; dB: decibels. *30 participants without access to Danish language IReST included in missing data rate.

Visual function measure	No AMD versus Early AMD		No AMD versus iAMD		No AMD versus Late AMD	
	Estimate (CI)	Adjusted p value	Estimate (CI)	Adjusted p value	Estimate (CI)	Adjusted p value
BCVA (LogMAR)	0.04 (-0.10, 0.08)	0.22	0.05 (0.02, 0.09)	0.0017	0.79 (0.74, 0.83)	<0.0001
	No AMD n = 56 Early AMD n = 34		No AMD n = 56 i AMD n = 584		No AMD n = 56 Late AMD n = 43	
LLVA (LogMAR)	0.03 (-0.03, 0.09)	0.47	0.08 (0.04, 0.12)	0.0004	0.77 (0.71, 0.83)	<0.0001
	No AMD n = 56 Early AMD n = 34		No AMD n = 56 i AMD n = 583		No AMD n = 56 Late AMD n = 43	
MAT (LogMAR)	0.03 (-0.03, 0.09)	0.47	0.06 (0.01, 0.10)	0.02	0.63 (0.57, 0.69)	<0.0001
	No AMD n = 56 Early AMD n = 34		No AMD n = 56 i AMD n = 584		No AMD n = 56 Late AMD n = 43	
PR-CS (LogCS)	-0.06 (-0.14, 0.02)	0.21	-0.14 (-0.19, -0.08)	<0.0001	-0.59 (-0.67, -0.52)	<0.0001
	No AMD n = 56 Early AMD n = 34		No AMD n = 56 i AMD n = 583		No AMD n = 56 Late AMD n = 43	
SPS (wpm)	-31 (-48, -14)	0.001	-10 (-21, 2)	0.17	-125 (-141, -109)	<0.0001
	No AMD n = 55 Early AMD n = 34		No AMD n = 55 i AMD n = 548		No AMD n = 55 Late AMD n = 39	
MesAT (dB)	-1.13 (-2.72, 0.46)	0.27	-1.69 (-2.73, -0.65)	0.004	-16.61 (-18.17, -15.05)	<0.0001
	No AMD n = 54 Early AMD n = 34		No AMD n = 54 i AMD n = 527		No AMD n = 54 Late AMD n = 37	
ScoAT (dB)	-1.41 (-3.04, 0.22)	0.17	-2.29 (-3.37, -1.21)	0.0001	-14.56 (-16.27, -12.84)	<0.0001
	No AMD n = 53 Early AMD n = 34		No AMD n = 53 i AMD n = 496		No AMD n = 53 Late AMD n = 29	
RIT (mins)	1.41 (-1.00, 3.82)	0.37	2.35 (0.72, 3.98)	0.01	8.32 (5.36, 11.28)	<0.0001
	No AMD n = 43 Early AMD n = 29		No AMD n = 43 i AMD n = 408		No AMD n = 43 Late AMD n = 16	

Table 2: Relationship between visual function measures and disease classification

Linear regression model examining the relationship between each visual function measure (as dependent variable) and disease classification, adjusted for age, sex and phakic status.

AMD: age-related macular degeneration; i: intermediate; BCVA: best corrected visual acuity; LLVA: low luminance visual acuity; MAT: Moorfields acuity test; PR-CS: Pelli-Robson contrast sensitivity; SPS: Small print standardised International Reading Speed Test; MesAT: Mesopic average threshold; ScoAT: Scotopic average threshold; RIT: Rod Intercept Time; LogMAR: logarithm of the minimum angle of resolution; LogCS: logarithm of contrast sensitivity; wpm: words per minute; dB: decibel, mins: minutes. Bold indicates significant result.

Visual function measure	Reference limit	n (%) of iAMD participants breaching reference limit	iAMD (mean $\pm$ SD)		No AMD (mean $\pm$ SD)	Δ iAMD (function impaired – no AMD)
			Function impaired	Function not impaired		
BCVA (LogMAR)	> 0.10	120 (20.5%)	0.18 (0.05)	-0.01 (0.08)	-0.04 (0.08)	0.22 (11 letters)
LLVA (LogMAR)	> 0.32	141 (24.1%)	0.46 (0.12)	0.18 (0.09)	0.14 (0.09)	0.32 (16 letters)
MAT (LogMAR)	> 0.55	136 (23.2%)	0.65 (0.09)	0.38 (0.12)	0.36 (0.11)	0.29 (14.5 letters)
PR-CS (LogCS)	< 1.49	183 (31.3%)	1.36 (0.12)	1.64 (0.12)	1.71 (0.16)	-0.35 (7 letters)
SPS (wpm)	< 100	74 (12.6%)	74 (23)	155 (29)	156 (38)	-82
MesAT (dB)	< 21.7	116 (19.8%)	18.2 (4.2)	24.8 (1.6)	25.4 (2.1)	-7.2
ScoAT (dB)	< 17.0	105 (17.9%)	12.9 (3.7)	20.3 (1.7)	21.3 (2.4)	-8.4
RIT (mins)	> 6.21	172 (29.4%)	12.10 (11.6)	4.39 (1.07)	4.24 (1.36)	-7.86

Table 3: Summary of iAMD participants breaching visual function reference limits

Number and proportion iAMD participants breaching the reference limit for each visual function test calculated as a proportion of the complete iAMD cohort (585). Mean $\pm$ standard deviation of those breaching the reference limited (functionally impaired) and not breaching the reference limit (function not impaired) for each variable. No AMD data provided for comparison between iAMD function impaired and no AMD.

BCVA: best corrected visual acuity; LLVA: low luminance visual acuity; MAT: Moorfields acuity test; PR-CS: Pelli-Robson contrast sensitivity; SPS: Small Print Standardised International Reading Speed Test; MesAT: Mesopic average threshold; ScoAT: Scotopic average threshold; RIT: Rod Intercept Time; LogMAR: logarithm of the minimum angle of resolution; LogCS: logarithm of contrast sensitivity; wpm: words per minute; dB: decibel, mins: minutes.

Number of reference limits breached	iAMD n (%)
0	178 (30.4%)
1	157 (26.8%)
2	92 (15.7%)
3	51 (8.7%)
4	37 (6.3%)
5	35 (6.0%)
6	19 (3.2%)
7	12 (2.1%)
8	4 (0.7%)

Table 4: Summary of iAMD participants breaching 0 – 8 reference limits

Number and proportion of iAMD participants breaching 0 through 8 worse than reference limits.

AMD: age-related macular degeneration; i: intermediate.

Visual function measure	n (%) with valid data	Reference Limit based on worse of V2 and V3	n (%) of iAMD participants breaching worse reference limit
BCVA	584 (99.8%)	> 0.11 LogMAR	120 (20.5%)
LLVA	583 (99.6%)	> 0.32 LogMAR	141 (24.1%)
MAT	584 (99.8%)	> 0.58 LogMAR	136 (23.2%)
PR-CS	583 (99.6%)	< 1.45 LogCS	183 (31.3%)
SPS	548 (93.7%)	< 97 wpm	74 (12.6%)
MesAT	527 (90.1%)	< 20.7 dB	116 (19.8%)
ScoAT	496 (84.8%)	< 16.2 dB	105 (17.9%)
RIT	408 (69.7%)	> 6.48 mins	172 (29.4%)

Table 5: Summary of secondary reference limits and proportion of iAMD participants breaching.

Number and proportion iAMD participants breaching secondary worse than reference limits for each visual function test calculated as a proportion of the complete iAMD cohort (585).

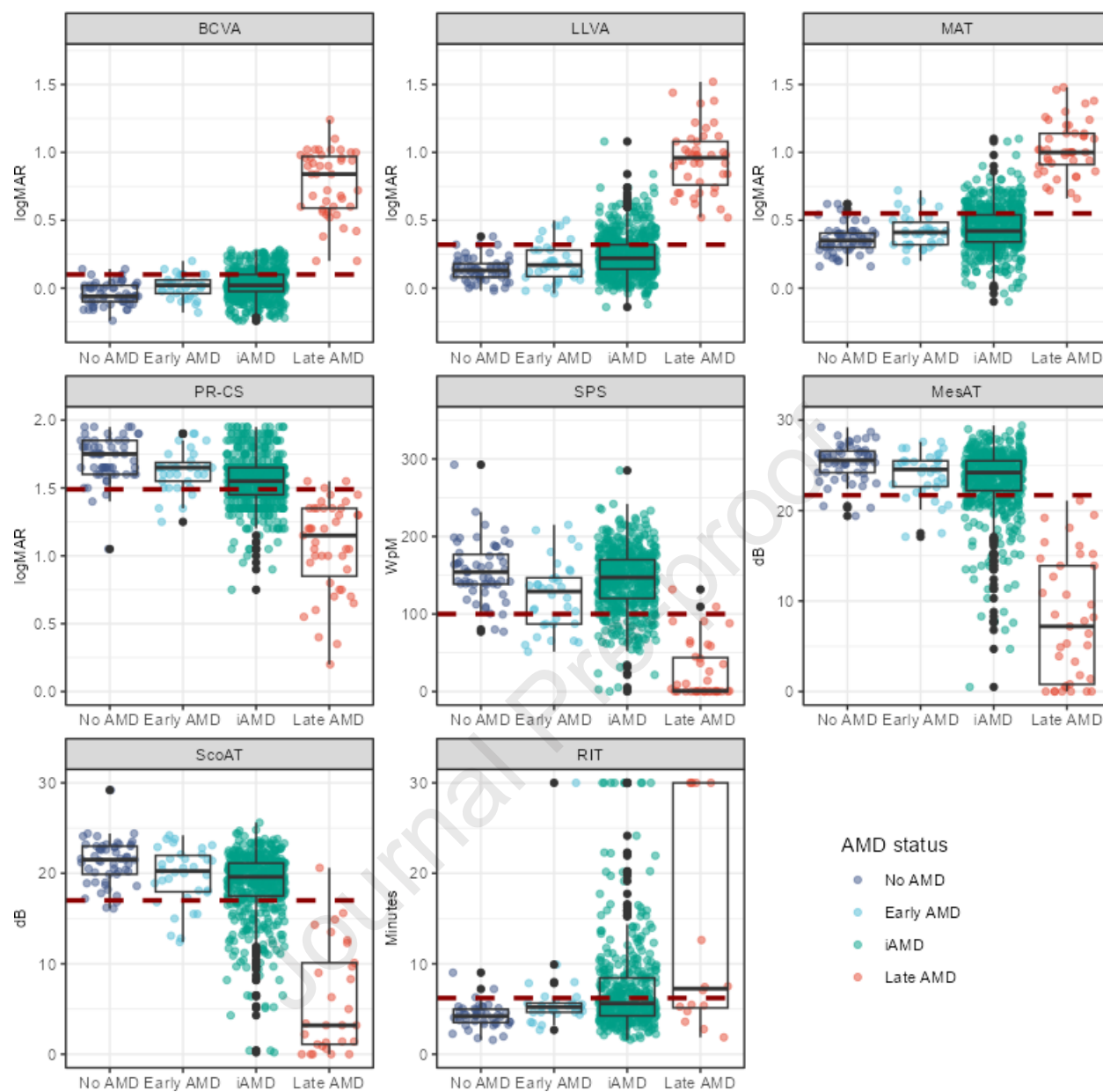
BCVA: best corrected visual acuity; LLVA: low luminance visual acuity; MAT: Moorfields acuity test; PR-CS: Pelli-Robson contrast sensitivity; SPS: Small Print Standardised International Reading Speed Test; MesAT: Mesopic average threshold; ScoAT: Scotopic average threshold; RIT: Rod Intercept Time; LogMAR: logarithm of the minimum angle of resolution; LogCS: logarithm of contrast sensitivity; wpm: words per minute; dB: decibel, mins: minutes.

Number of reference limits breached	iAMD n (%)
0	225 (38.5%)
1	151 (25.8%)
2	84 (14.4%)
3	44 (7.5%)
4	31 (5.3%)
5	27 (4.6%)
6	11 (1.8%)
7	10 (1.7%)
8	2 (0.3%)

Table 6: Summary of iAMD participants breaching 0 – 8 secondary reference limits

Number and proportion iAMD participants breaching 0 through 8 secondary worse than reference limits.

AMD: age-related macular degeneration; i: intermediate.



Précis

In the MACUSTAR study, multiple tests of clinical visual function reveal functional heterogeneity in intermediate age-related macular degeneration which is relevant to future trial design.

Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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