

ORIGINAL ARTICLE

# Vision and Mobility Performance of Subjects with Age-Related Macular Degeneration

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**ABSTRACT:** *Purpose.* To investigate the effects of age-related macular degeneration (ARMD) on mobility performance and to identify the vision determinants of mobility in subjects with ARMD. *Methods.* Walking speed and the number of obstacle contacts made on a 79-m indoor mobility course were measured in 21 subjects with ARMD and 11 age-matched subjects with normal vision. The mobility measures were transformed to percentage preferred walking speed and contacts score. The vision functions assessed included binocular visual acuity, contrast sensitivity, and visual field. *Results.* In this study, subjects with ARMD did not walk significantly slower or make significantly more obstacle contacts on the mobility course than the normally sighted subjects of similar age. Between 29% and 35% of the variance in the ARMD mobility performance was accounted for by visual field and contrast sensitivity measures. The most significant predictor of mobility performance scored as percentage preferred walking speed was the size of a binocular central scotoma. *Conclusion.* As the size of a binocular central scotoma increases, mobility performance decreases. (*Optom Vis Sci* 2002;79:697-707)

Key Words: mobility, age-related macular degeneration, binocular scotoma

Age-related macular degeneration (ARMD) is the leading cause of visual impairment in industrialized countries.<sup>1-4</sup> This eye disease results in the development of central scotomas and impairs macular functions causing reduced visual acuity (VA), contrast sensitivity (CS), and delayed photostress recovery time.<sup>5-9</sup> The functional implications of this type of vision loss mainly include problems with reading, seeing television, and face recognition.<sup>10-12</sup> However, the effects of ARMD on mobility performance, another important activity of daily living, have been investigated in only a few studies.

Brown et al.<sup>13</sup> and Wilcox and Burdett<sup>14</sup> found that under high luminance conditions, subjects with ARMD had no more difficulty with mobility than did subjects of similar age with normal vision. However, the simplicity of their mobility course designs may have contributed to their findings. This suggestion is supported by the investigation of Kuyk and Elliott,<sup>15</sup> who found that subjects with ARMD walked faster on their simplest mobility course than they did on more difficult routes. The significance of mobility course complexity on mobility performance has also been demonstrated for subjects with other types of ocular pathology such as retinitis pigmentosa.<sup>16</sup> In addition, the mobility courses of Brown et al.<sup>13</sup> and Wilcox and Burdett,<sup>14</sup> unlike those of the

majority of recent mobility studies,<sup>15, 17, 18</sup> did not include various-sized obstacles scattered directly in the subject's direction of travel. Brown et al.<sup>13</sup> used three different mobility courses that were variations of a path that used poles as navigational cues to outline the course. Similarly, the mobility course used by Wilcox and Burdett<sup>14</sup> was simply an outlined path with no obstacles. "Real-world" mobility requires subjects to avoid obstacles to safely navigate and travel along a path.

Kuyk and Elliott<sup>15</sup> found that the mobility performance of ARMD subjects was significantly worse under reduced illumination compared with high-illuminance conditions. However, they did not include an age-matched control group in their study and thus were unable to conclude whether the ARMD subjects demonstrated impaired mobility compared with normally sighted subjects of similar age. Despite this, unlike the studies of Brown et al.<sup>13</sup> and Wilcox and Burdett,<sup>14</sup> Kuyk and Elliott<sup>15</sup> assessed a large number of vision and perceptual functions in subjects with ARMD. As a result, the study by Kuyk and Elliott<sup>15</sup> has been the only systematic investigation assessing the predictive value of numerous vision and perceptual functions in the mobility performance of subjects with ARMD. They found that from a multivariable predictor model, Pelli-Robson letter contrast sensitivity and

visual field (VF) extent were the best predictors of the time taken and the number of contacts with obstacles, respectively, on their indoor obstacle course. Brown et al.<sup>13</sup> found that VA and VF together with differential velocity discrimination accounted for 86% of the variance in mobility performance for subjects with ARMD, but they did not assess contrast sensitivity, which has since been identified by Kuyk and Elliott<sup>15</sup> to be a significant predictor of mobility performance in subjects with ARMD. In contrast, Wilcox and Burdett<sup>14</sup> found no correlation between mobility and contrast sensitivity and VA and did not assess the VF. Differences in findings between these earlier ARMD mobility studies may be attributed to the different methodologies used. Each of these studies have investigated ARMD subjects with varying degrees of vision loss, have assessed different vision measures scored by a variety of methods, and have used mobility courses of varying complexity.

Another limitation of all earlier studies assessing the mobility performance of subjects with ARMD is the lack of comprehensive investigations into the effects of a central scotoma on mobility performance. Wilcox and Burdett<sup>14</sup> did not assess the VF of their ARMD subjects, and Kuyk and Elliott<sup>15</sup> only measured VF extent and therefore did not measure and score the size of a central scotoma. Brown et al.<sup>13</sup> however indirectly assessed scotoma size in their ARMD subjects because their VF measures were based on the number of points detected, which presumably included an assessment of points in the central VF. Although Brown et al.<sup>13</sup> found significant correlations between the mobility performance of ARMD subjects and their VF measures, they may have obtained stronger correlations if a direct measure of central scotoma size were used. Because ARMD is characterized by the presence of a central scotoma, assessments should be made into how the mobility performance of subjects with ARMD varies as a function of scotoma size.

Because the number of people with visual impairment due to ARMD will increase world-wide<sup>19–22</sup> and only a few, limited studies have evaluated the relationship between vision and mobility in subjects with ARMD, we compared the mobility performance of subjects with ARMD with that of normally sighted subjects of similar age using an indoor, high-density obstacle course. We also explored the relationship between scotoma size and mobility performance and identified the vision function(s) that best predicted the mobility performance of subjects with ARMD. We hypothesized that as found in earlier mobility studies assessing subjects with either ARMD<sup>15</sup> or with other types of ocular pathology,<sup>16, 23–25</sup> measures of VF and contrast sensitivity would emerge as the best predictors of mobility for subjects with ARMD. Also, in agreement with the results of Kuyk and Elliott<sup>15</sup> for mobility performance assessed using ARMD subjects on a complex, highly illuminated course, we hypothesized that the ARMD subjects would not experience more difficulty with mobility than the normally sighted subjects of similar age.

## METHODS

### Subjects

Twenty-one subjects with ARMD and 11 subjects of similar age with normal vision (control subjects) were tested (Table 1). ARMD subjects, who had a confirmed diagnosis of ARMD from an optometrist and/or ophthalmologist, were recruited from the

clinical records of the Queensland University of Technology Vision Rehabilitation Centre. Normally sighted subjects were recruited either from the clinical records of the Queensland University of Technology Optometry Clinic, from a database of people who had participated in earlier, unrelated studies conducted at the Queensland University of Technology Centre for Eye Research, or through a relationship with another subject. To screen for subject suitability in normally sighted subjects not recruited from the Queensland University of Technology Optometry Clinic, the findings of their latest eye examination were obtained from their eye care practitioner. Subjects were excluded on the basis of any ocular disease other than ARMD or if a physical or cognitive disorder was considered as significantly affecting their mobility, vision performance, or their ability to follow instructions. This information was obtained through written observations from the subject's clinical record (including general health and prescribed medications and their current mental state as assessed by a social worker) and through telephone interviews. The ages of the ARMD subjects ranged from 66 to 87 years (average,  $79.7 \pm 5.3$ ), and the ages of the control subjects ranged from 66 to 86 years (average,  $77.1 \pm 6.7$ ) (Table 1). There were no significant differences in the age distribution (Mann-Whitney U test,  $z = -1.2$ ;  $p = 0.23$ ) or the mean age (independent t-test,  $t_{30} = -1.2$ ;  $p = 0.23$ ) between the two subject groups. The research followed the tenets of the Declaration of Helsinki and was approved by the Queensland University of Technology Human Research Ethics Committee. Informed consent was obtained from each subject after the nature and possible consequences of the study had been described.

### Vision Assessment

All vision assessments were performed binocularly using the subject's habitual spectacle correction and were measured once, unless otherwise specified, over two experimental sessions between 1 and 3 weeks apart. The ARMD subjects were encouraged to use their habitual fixation (central or eccentric) for all vision measures. High- (93%) and low-contrast (14%) VA were measured using Bailey-Lovie charts at test distances that allowed at least the first two lines of the chart to be correctly identified. The background illuminances of the high- and low-contrast Bailey-Lovie charts were 293 lux and 284 lux, respectively, and binocular VA was scored letter-by-letter and expressed in logarithm of the minimum angle of resolution (logMAR) notation.<sup>26</sup> High-contrast VA was measured again at the second experimental session to ensure that no subject had a significant loss of acuity ( $\geq 0.1$  logMAR) between sessions.<sup>27</sup> The second high-contrast VA measurement was used for analysis.

Contrast sensitivity was assessed using the Pelli-Robson letter contrast sensitivity chart,<sup>28</sup> the Melbourne Edge Test (MET),<sup>29</sup> and sine wave gratings presented on a video monitor. Pelli-Robson letter contrast sensitivity was measured at 1 m with a chart illuminance of 103 lux, and subjects were asked to guess letters until one complete line (six letters) was read incorrectly. Each correctly identified letter was assigned a value of 0.05 log contrast sensitivity and a call of "O" for "C" was accepted as correct.<sup>30, 31</sup> MET contrast sensitivity, which is a three-alternative forced-choice psychometric measure of square-wave contrast sensitivity, was measured by asking subjects to identify the orientation of a series of edges, the

**TABLE 1.**Characteristics of the 21 subjects with ARMD and the 11 age-matched normally sighted (control) subjects<sup>a</sup>

ARMD Subjects					Control Subjects			
ID	Gender	Age (yr)	HCVA (logMAR)	BinocSco Extent <sup>b</sup> (deg)	ID	Gender	Age (yr)	HCVA (logMAR)
AH	M	82.2	0.78	6.8 ± 1.4	AC	M	77.2	0.06
BO	F	76.2	0.66	8.6 ± 3.4	BB	F	79.1	0.04
CL	F	66.1	1.00	9.4 ± 2.3	EC	F	78.5	0.06
DD	F	84.1	1.12	12.6 ± 6.0	GC	M	86.1	0.06
DM	M	79.4	0.86	3.0 ± 0.0	JM	M	77.0	0.10
FB	M	77.9	0.98	6.7 ± 1.4	MC1	F	79.8	0.00
FH	F	79.9	0.38	6.6 ± 1.4	ML	F	86.4	-0.08
FS	F	79.0	1.44	7.7 ± 6.7	PB1	M	80.2	0.06
FS1	M	81.7	0.22	0.0 ± 0.0	PP	M	68.5	-0.02
GB	F	87.2	0.88	8.7 ± 2.2	RK	M	68.4	-0.06
HP	F	67.5	0.22	0.0 ± 0.0	RR	F	66.6	-0.04
LS	F	76.0	1.22	8.5 ± 2.3				
MC	F	80.4	1.28	6.7 ± 1.5				
MG	F	77.7	0.44	0.0 ± 0.0				
NC	M	84.5	1.02	13.5 ± 5.8				
RH	M	82.2	1.14	9.9 ± 4.2				
US	F	78.3	1.24	12.3 ± 7.2				
VC	M	86.7	0.92	11.9 ± 5.2				
VF	M	80.9	0.74	11.1 ± 2.1				
WB	F	84.1	0.18	0.0 ± 0.0				
WD	F	81.8	1.08	12.0 ± 2.8				
Mean ± SD	13 F 8 M	79.7 ± 5.3	0.85 ± 0.37	7.4 ± 4.5	—	5 F 6 M	77.1 ± 6.7	0.02 ± 0.06

<sup>a</sup> ARMD, age-related macular degeneration; HCVA, high-contrast visual acuity; logMAR, logarithm of the minimum angle of resolution.

<sup>b</sup> Binoc Sco Extent, extent of binocular scotoma (radius); measured using the Humphrey Field Analyzer and averaged across all measured meridians. For ease of interpretation, the units of measurement have been converted from solid angle (steradians) to degrees of visual angle. By definition, the age-matched control subjects had no binocular scotoma.

contrast of which decreased with each successive “patch,” until three consecutive errors were made. The chart illuminance was 264 lux, and subjects were optically corrected for the 40-cm test distance. The MET contrast sensitivity score, in decibels, was the lowest contrast patch correctly identified.<sup>29</sup>

Sine-wave contrast sensitivity was measured for vertical sinusoidal gratings at five spatial frequencies: 0.5, 1.0, 2.0, 4.0, and 8.0 cpd. The gratings were displayed on a video monitor and presented randomly interleaved. Subjects were required to indicate the presence or absence of sinusoidal gratings with a “yes/no” response, and sinusoidal gratings were presented using a criterion-dependent (staircase) procedure. To reduce spatial frequency uncertainty,<sup>32</sup> a tone preceded each presentation, where tone varied in pitch with spatial frequency. The luminance of the surround was matched to the screen luminance of 45 cd/m<sup>2</sup>. Contrast sensitivity was measured at 3 m for all subjects except five ARMD subjects, who viewed the gratings from 1 m. The shorter test distance provided a larger stimulus (i.e., visual angle of the grating area) but the same spatial frequencies. Contrast threshold was defined as the 50% seeing point on the psychometric function and was determined using Adaptive Probit Estimation.<sup>33</sup> At the completion of a trial, a full probit analysis calculated log contrast sensitivity for each spa-

tial frequency assessed. Peak contrast sensitivity was recorded as the highest contrast sensitivity irrespective of spatial frequency.

The binocular VF was assessed by kinetic (Tangent screen and Humphrey Field Analyzer [HFA]) and static (HFA) methods. The central 25° radius VF was measured along 12 meridians with a 5/1000 W target on a Tangent screen of illuminance 112 lux. Subjects wore their own distance prescription, and habitual fixation (central or eccentric) was maintained by instructing subjects to fixate on a large, centrally located letter “E” target.<sup>34</sup> The extent of the central VF and the position and size of any central scotoma were recorded. The VF was scored as the solid angle subtended by the binocular scotoma and as the remaining central VF, calculated as the difference between the solid angle subtended by the subject’s central VF extent and that subtended by the scotoma. In addition, subjects were categorized into two groups according to the presence or absence of a binocular scotoma to the 5/1000 W target. Using this classification system, six subjects with ARMD were identified as having no binocular scotoma.

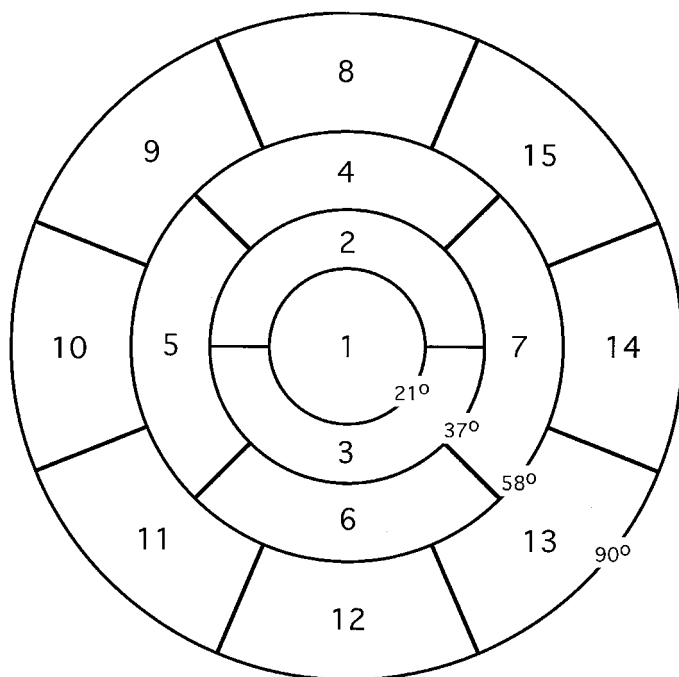
The full binocular VF was also assessed from radii of 55° vertically and 75° horizontally using the HFA kinetic program with IV 4E<sup>macr</sup> target on a background luminance of 10 cd/m<sup>2</sup>. Subjects were instructed to fixate (habitual central or eccentric) on a central

“E” target attached to the HFA bowl, and visual field extent was measured along 28 meridians. To avoid the lens rim affecting the VF result,<sup>35</sup> no optical correction was worn for this assessment of the peripheral VF extent. A scotoma was identified if the subject did not detect a static light presented for 1 s within the central VF. The scotoma was mapped in the eight principal meridians by moving the target from the unseen point until the subject indicated its detection. Subjects were optically corrected for the 33-cm test distance for the scotoma identification and mapping. The HFA kinetic VF was measured once at each of the two experimental sessions: the first measure served as practice, and the second result was used for analysis. The HFA kinetic VF was scored in the same manner as the Tangent screen result as well as using a technique described by Lovie-Kitchin et al.,<sup>36</sup> in which kinetic annular VF scores were calculated for every subject as the percent remaining VF in each of 15 zones of equal solid angle (Fig. 1).

The central VF was also assessed to static stimuli using the HFA Fastpac Threshold 30-2 program with the Goldmann III white target and background luminance of 10 cd/m<sup>2</sup>. Fixation was again controlled using the “E” target attached to the HFA bowl, and subjects were optically corrected for the 33-cm test distance. Static VF results were scored by averaging sensitivities (dB) for the entire VF as well as for the central 10° zone and for the superior and inferior hemifields for the central 20° and 30°.

## Mobility Assessment

Before assessing mobility, the independent travel technique was used to determine subjects’ preferred walking speed.<sup>23, 37</sup> Subjects were timed as they walked along a 20-m straight, unobstructed, level corridor at their normal, comfortable pace. This was repeated four times, and the subject’s preferred walking speed, in meters per



**FIGURE 1.**

The 15 HFA Kinetic Annular VF Zones of Lovie-Kitchin et al.<sup>36</sup> Each zone subtends an equal solid angle.

second, was computed as the mean of the last three trials because subjects walked significantly slower on the first preferred walking speed trial compared with the other three trials (repeated measures analysis of covariance,  $F_{(1,20)} = 732.9$ ,  $p < 0.001$ ; Bonferroni *post hoc* test,  $p < 0.01$ ).

Mobility performance was assessed on a high-density indoor obstacle course (see Fig. 1 illustrated in Soong et al.,<sup>38</sup> constructed at the Queensland University of Technology Centre for Eye Research laboratories, as previously described in Hassan et al.<sup>39</sup> In summary, the course consisted of a pathway 79 m long and 1.2 m wide outlined using high-reflectance folded plastic bubble-wrap. The course was divided into four stages ranging from approximately 6 m to 31 m (Table 2) and included a step, ramp, and an “open area” approximately 3.4 m long and 2.4 m wide bordered by large plastic sheets to simulate a pathway between two walls. Illumination was in the photopic range (approximately 300 to 500 lux) with the exception of one room (the “glare” room) where the average illuminance was 52 lux. In that room, a glare source directed at the room entrance was provided by a 60-W spotlight positioned in the middle of the otherwise darkened room. One hundred obstacles of varying sizes and heights were purposely positioned along the travel path, resting either on the floor or on tables or suspended from the ceiling. There were unequal numbers of obstacles per meter of the mobility course and the “open area” was obstacle free. Obstacles were made of foam, cardboard, paper, or plastic and were classified into five different height levels ranging from the floor (level 1 obstacles) to >149 cm high (level 5 obstacles) (refer to Soong et al.<sup>38</sup> for a detailed description of obstacle height categories). Within each obstacle classification, there were 10 high-luminance (light gray) and 10 low-luminance (black) obstacles. Subjects were also required to perform two tasks at different stages along the mobility course. Task 1 involved subjects placing a small packet, given to them at the start of the mobility course, on a bench labeled “Table 1.” Task 2 required subjects to locate a table with three shopping items and an empty bag. Subjects had to fill the bag with all three items and carry it until they located a sign-posted table positioned near the end of the course.

The mobility performance measures included percentage preferred walking speed (PPWS) and the number and type of obstacles contacted during the walk. PPWS was the ratio of a subject’s walking speed (meters per second) around the course to their preferred

**TABLE 2.**  
The mobility course stages

Stage	Description of Stage	Distance (m)
a	From start of course up to and including the bench labeled as “Table 1”	31.2
b	From completion of “Table 1” to start of “glare” room	24.0
g	From start of “glare” room to end of “glare” room	6.1
c	From end of “glare” room to finish of mobility course (contains Task 2)	17.6
Total	The entire path length from start to finish	78.9

walking speed expressed as a percentage.<sup>40</sup> PPWS was recorded for each stage of the mobility course as well as for the whole course. Subjects were instructed to walk the course at their own comfortable pace, staying within the boundary and avoiding all obstacles in their path.

The total number of obstacle contacts averaged over the entire course for each obstacle height category and luminance category for both subject groups were transformed into contacts scores using the following equation<sup>25</sup>:

$$\text{contacts score} = \text{Log}_{10} [100 / (1 + \text{number of contacts})]$$

## Data Analysis

To assess the effects of the different stages of the mobility course and for differences between subject groups in PPWS performance, an analysis of covariance controlling for age was performed. Differences in contacts scores between subject groups for each obstacle height and luminance category as well as for the whole course were assessed using an exact inference version of the Mann-Whitney U test. Exact inference was used because of the relatively small sample size and the high proportion of subjects with the same contacts score.<sup>41</sup> It should be noted that exact inference does not produce a z score because the distribution of the statistic is calculated from the actual data set as opposed to standardizing the data to a normal (0,1) distribution.<sup>41</sup> As a result, only a p value will be reported for results pertaining to contacts score analyzed using the exact inference version of the Mann-Whitney U test. It was not appropriate to use the exact inference version of the Mann-Whitney U test when assessing the effect of obstacle luminance and height on the mobility performance of the ARMD subjects because two independent samples were not being analyzed (i.e., these analyses involved only the ARMD subjects). For this reason, the Wilcoxon matched pairs signed ranked test and the Kruskal-Wallis one-way analysis of variance were used to assess the effects of obstacle luminance and height on the ARMD subjects, respectively.

Pearson or Spearman correlation coefficients (as appropriate for normally distributed and non-normally distributed variables, respectively) were computed to assess which vision measure(s) correlated with mobility performance. Due to the large number of correlations performed, the number of comparisons exceeded the degrees of freedom associated with the variables. Consequently, for correlations, the modified Bonferroni test was applied to produce a more stringent p value of 0.02.<sup>42</sup> To determine which vision measure(s) best predicted mobility performance, four forward stepwise linear multiple regression analyses (MRA's) were performed. The four-stage MRA's reduced the number of independent variables, thereby increasing the reliability of the MRA models.

The first three MRA's determined which VF measures were the best predictors of mobility performance from three variable sets: (1) static VF measures, (2) seven kinetic annular VF zones, and (3) the significant VF predictors of the preceding two MRA's along with the size of the remaining VF and size of a binocular scotoma as measured using the HFA and tangent screen. The seven kinetic annular zones were selected on the basis of the results of Lovie-Kitchin et al.<sup>36</sup> and from the results of the Pearson and Spearman correlations. The final (fourth) regression determined which vision

measure(s) best predicted mobility performance by using the significant VF predictors from the third MRA in conjunction with the remaining vision measures (i.e., high- and low-contrast VA, MET contrast sensitivity, Pelli-Robson contrast sensitivity, and contrast sensitivity at five spatial frequencies). The above MRA's were performed for both PPWS and contacts score averaged over the entire mobility course (PPWS<sub>total</sub> and contacts score<sub>total</sub>, respectively).

All MRA's were examined for a range of possible problems including multicollinearity, outliers, normality, and an even spread of residuals. The reported multiple coefficients of determination (R<sup>2</sup>) were adjusted for the number of terms and sample size.

## RESULTS

### Vision Performance: ARMD Subjects vs. Control Subjects

As expected, the ARMD group had significantly worse performance than the normally sighted group on the majority of vision measures when controlled for age (multiple analysis of covariance,  $F_{1,27} > 6.3$ ,  $p < 0.018$ ; for non-normally distributed data, Mann-Whitney U test,  $z < -2.42$ ,  $p < 0.016$ ) (Table 3). The exceptions to this were kinetic annular VF scores in the inferior (zone 3, Fig. 1), the superior left (zone 9, Fig. 1), and the inferior left (zone 11, Fig. 1) VF zones (Mann-Whitney U test,  $z > -1.72$ ,  $p > 0.08$ ). This suggests that there was considerable overlap in the distributions of these VF scores between the ARMD and control groups; few subjects' VF extended into zones 9 and 11, and the majority of subjects had a "full" VF in zone 3.

### Mobility Performance: ARMD Subjects vs. Control Subjects

The average preferred walking speed of the ARMD group was not significantly different from that of the normally sighted group (analysis of covariance,  $F_{(1,29)} = 0.89$ ,  $p = 0.35$ ) (Table 4). Preferred walking speed also varied with age (weakly significant covariate,  $t_{31} = -2.35$ ,  $p = 0.03$ ). Therefore, older ARMD and normally sighted subjects demonstrated slower preferred walking speed values than younger subjects.

Mean PPWS of the ARMD group was slightly lower, but not significantly from that of the normally sighted group (analysis of covariance,  $F_{(1,29)} = 3.56$ ,  $p = 0.07$ ) (Table 4). PPWS was different for different stages of the mobility course ( $F_{(3,90)} = 75.11$ ,  $p < 0.001$ ), although the effect was similar for each group ( $F_{(3,90)} = 0.54$ ,  $p = 0.66$ ) (Table 4 and Fig. 2). In general, the mobility performance of all subjects was significantly impaired under conditions of reduced illumination and glare (stage g, Fig. 2). The debilitating light conditions of stage g along with the time required to complete task 2 may have also reduced the mobility performance of both subject groups in the stage after the glare room (stage c, Fig. 2). PPWS in stage c was significantly lower than PPWS in stages a and b for both groups (Duncan's multiple range test,  $p < 0.05$ ). There were no significant differences in PPWS between the high illuminance conditions of stages a and b for either subject group (Duncan's multiple range test,  $p > 0.05$ ) (Fig. 2).

ARMD subjects did not make significantly more obstacle contacts on the course (contacts score<sub>total</sub>) than the normally sighted subjects

**TABLE 3.**Vision scores for the 21 ARMD and 11 normally sighted (control) subjects<sup>a,b</sup>

Vision Variable	ARMD Group	Control Group
High Contrast Bailey-Lovie Acuity (logMAR)	0.85 ± 0.37	0.02 ± 0.06
Low Contrast Bailey-Lovie Acuity (logMAR)	1.16 ± 0.44	0.28 ± 0.11
Pelli-Robson Letter Contrast Sensitivity (log CS)	1.06 ± 0.35	1.73 ± 0.13
Melbourne Edge Test (dB)	11.6 ± 4.2	21.8 ± 2.0
Log Contrast Sensitivity at 0.5 cpd	1.1 ± 0.2	1.8 ± 0.1
Log Contrast Sensitivity at 1.0 cpd	1.3 ± 0.3	2.0 ± 0.1
Log Contrast Sensitivity at 2.0 cpd	1.3 ± 0.4	2.3 ± 0.3
Log Contrast Sensitivity at 4.0 cpd	0.9 ± 0.6	2.2 ± 0.3
Log Contrast Sensitivity at 8.0 cpd	0.6 ± 0.5	2.0 ± 0.3
Peak Log Contrast Sensitivity	1.4 ± 0.3	2.4 ± 0.3
Solid Angle of Binocular Scotoma measured using the Tangent Screen with 5/1000 W Bjerrum Target (steradians)	0.01 ± 0.02	0.0 ± 0.0
Solid Angle of Remaining Tangent Screen Visual Field measured with 5/1000 W Bjerrum Target (steradians)	0.54 (0.4, 0.57)	0.57 (0.57, 0.57)
Solid Angle of Binocular Scotoma measured using the Humphrey Field Analyzer (steradians)	0.07 ± 0.06	0.0 ± 0.0
Solid Angle of Remaining Humphrey Field Analyzer Visual Field (steradians)	1.8 ± 0.6	2.5 ± 0.4
Percent Remaining Visual Field in Zone 1 (%)	86.3 (0.0, 100.0)	100.0 (100.0, 100.0)
Percent Remaining Visual Field in Zone 2 (%)	75.3 ± 29.6	94.1 ± 10.4
Percent Remaining Visual Field in Zone 3 (%)	100.0 (49.4, 100.0)	100.0 (100.0, 100.0)
Percent Remaining Visual Field in Zone 4 (%)	11.1 ± 14.8	20.9 ± 20.9
Percent Remaining Visual Field in Zone 5 (%)	54.3 ± 30.6	81.2 ± 18.8
Percent Remaining Visual Field in Zone 6 (%)	38.0 ± 28.1	72.8 ± 9.0
Percent Remaining Visual Field in Zone 7 (%)	58.9 ± 25.1	83.4 ± 13.6
Percent Remaining Visual Field in Zone 8 (%)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)
Percent Remaining Visual Field in Zone 9 (%)	0.0 (0.0, 6.12)	0.0 (0.0, 11.1)
Percent Remaining Visual Field in Zone 10 (%)	7.5 ± 10.9	14.4 ± 11.7
Percent Remaining Visual Field in Zone 11 (%)	0.0 (0.0, 13.8)	6.1 (0.0, 14.6)
Percent Remaining Visual Field in Zone 12 (%)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)
Percent Remaining Visual Field in Zone 13 (%)	0.0 (0.0, 0.0)	5.3 (0.0, 13.5)
Percent Remaining Visual Field in Zone 14 (%)	7.0 ± 8.2	12.7 ± 12.5
Percent Remaining Visual Field in Zone 15 (%)	0.0 (0.0, 0.0)	0.0 (0.0, 4.1)
Mean Sensitivity of entire Humphrey Field Analyzer 24-2 Static Visual Field (dB)	20.5 ± 4.3	28.0 ± 1.0
Mean Sensitivity of Humphrey Field Analyzer 24-2 Static Visual Field by central 10° (dB)	21.6 ± 5.2	31.5 ± 1.4
Mean Sensitivity of Humphrey Field Analyzer 24-2 Static Visual Field by superior 20° hemifield (dB)	20.9 ± 5.7	29.9 ± 1.1
Mean Sensitivity of Humphrey Field Analyzer 24-2 Static Visual Field by inferior 20° hemifield (dB)	23.9 ± 3.3	30.8 ± 1.3
Mean Sensitivity of Humphrey Field Analyzer 24-2 Static Visual Field by superior 30° hemifield (dB)	18.5 ± 5.4	26.5 ± 1.8
Mean Sensitivity of Humphrey Field Analyzer 24-2 Static Visual Field by inferior 30° hemifield (dB)	22.7 ± 3.6	29.0 ± 1.1

<sup>a</sup> Normally distributed results are presented as mean ± 1 SD. Non-normal distributions are presented as median (range: lowest score, highest score). The visual field zones are shown in Fig. 1.

<sup>b</sup> ARMD, age-related macular degeneration; logMAR, logarithm of the minimum angle of resolution; CS, contrast sensitivity.

(exact inference of Mann-Whitney U test,  $p = 0.31$ ) (Table 4). Contacts with high- and low-luminance obstacles were slightly, but not significantly, more common for the ARMD group than for the normally sighted group (exact inference of Mann-Whitney U test,  $p = 0.07$  for both the high- and low-luminance obstacles) (Table 4). Also, ARMD subjects contacted high-luminance obstacles at about the same frequency as low-luminance obstacles (Wilcoxon matched-pairs signed rank test,  $z = -0.18$ ,  $p = 0.86$ ).

The ARMD group contacted all five levels of obstacle heights as frequently as the normally sighted group (exact inference Mann-

Whitney U test,  $p > 0.12$ ). Additionally, for ARMD subjects there were small, but not significant, differences in the contacts scores between the obstacles of the five height categories (Kruskal-Wallis one-way analysis of variance,  $\chi^2_4 = 8.5$ ,  $p = 0.08$ ).

### Predicting ARMD Mobility Performance from Vision Measures

PPWS<sub>total</sub> correlated significantly ( $p \leq 0.02$ ) with low-contrast VA, sine-wave contrast sensitivity at all spatial frequencies except

**TABLE 4.** Mobility scores for the 21 ARMD and 11 normally sighted (control) subjects.<sup>a,b</sup>

Mobility Measure	ARMD Group	Control Group
Preferred walking speed (ms <sup>-1</sup> )	1.1 ± 0.2	1.3 ± 0.3
Percentage preferred walking speed in stage a (%)	50.7 ± 11.3	57.5 ± 9.4
Percentage preferred walking speed in stage b (%)	47.2 ± 12.3	55.8 ± 9.4
Percentage preferred walking speed in stage g (%)	28.8 ± 10.5	35.3 ± 6.0
Percentage preferred walking speed in stage c (%)	35.6 ± 9.4	39.8 ± 8.9
Percentage preferred walking speed over entire mobility course (%)	42.2 ± 9.0	46.4 ± 10.8
Contacts score for the number of high-luminance obstacles contacted	2.0 (1.3, 2.0)	2.0 (1.7, 2.0)
Contacts score for the number of low-luminance obstacles contacted	2.0 (1.3, 2.0)	2.0 (1.7, 2.0)
Contacts score for the total number of obstacles contacted	1.7 (1.05, 2.0)	2.0 (1.4, 2.0)
Contacts score for the number of level 1 obstacles contacted	2.0 (1.4, 2.0)	2.0 (2.0, 2.0)
Contacts score for the number of level 2 obstacles contacted	2.0 (1.7, 2.0)	2.0 (2.0, 2.0)
Contacts score for the number of level 3 obstacles contacted	2.0 (1.52, 2.0)	2.0 (2.0, 2.0)
Contacts score for the number of level 4 obstacles contacted	2.0 (1.52, 2.0)	2.0 (2.0, 2.0)
Contacts score for the number of level 5 obstacles contacted	2.0 (1.4, 2.0)	2.0 (1.4, 2.0)

<sup>a</sup> Normally distributed results are presented as mean ± 1 SD. Non-normal distributions are presented as median (range: lowest score, highest score). Derivation of the contacts score is shown in Equation 1.

<sup>b</sup> ARMD, age-related macular degeneration.

at 0.5 and 1.0 cpd, peak sine wave contrast sensitivity, and with the size of the binocular scotoma as measured using the HFA (Table 5). Contacts score<sub>total</sub> correlated significantly only with contrast sensitivity at 2 cpd (Table 5).

In assessing which vision measure(s) best predicted the mobility performance of subjects with ARMD (the fourth MRA, Table 6), the size of a binocular scotoma measured using the HFA was the sole predictor of PPWS<sub>total</sub>, explaining 30% of the variance. Contacts score<sub>total</sub> was best predicted by sine wave contrast sensitivity at 2.0 cpd, accounting for 35% of the variance. No other vision variables improved the prediction of mobility performance above that given by these VF and contrast sensitivity measures. Scatter plots for the size of a binocular scotoma (measured using the HFA) and the logarithm of contrast sensitivity at 2.0 cpd against PPWS<sub>total</sub> and contacts score<sub>total</sub> are shown in Figs. 3 and 4, respectively. Fig. 3 shows that as the size of a binocular scotoma increased, mobility performance becomes less efficient, as evidenced by decreased PPWS values. Fig. 4 shows that as contrast

sensitivity at 2.0 cpd increased, mobility performance increased because higher contacts scores equates to fewer obstacle contacts.

**DISCUSSION**  
**Mobility Performance of Subjects with ARMD**

The results of this experiment support the conclusions of Brown et al.<sup>13</sup> and Wilcox and Burdett<sup>14</sup> that as a group, people with ARMD do not demonstrate impaired mobility performance com-

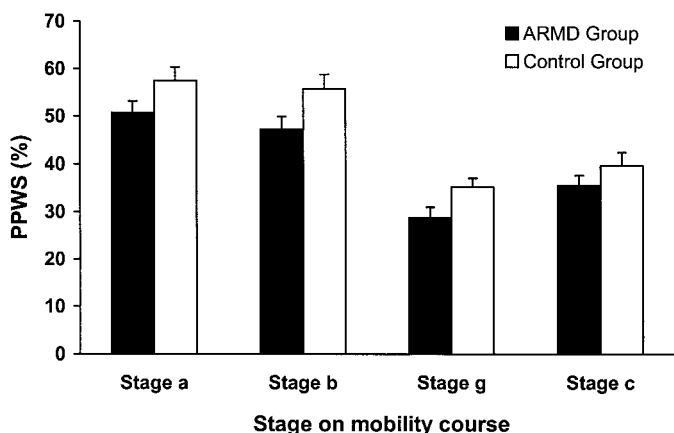
**TABLE 5.** Significant correlation coefficients (p ≤ 0.02) of the vision measures and mobility performance for ARMD subjects only<sup>a</sup>

Vision Measure	Pearson Correlation Coefficient PPWS <sub>total</sub>	Spearman Correlation Coefficient Contacts Score <sub>total</sub>
LCVA	-0.55 <sup>b</sup>	NS
LogCS2.0	0.53 <sup>c</sup>	0.56 <sup>b</sup>
LogCS4.0	0.56 <sup>b</sup>	NS
LogCS8.0	0.57 <sup>b</sup>	NS
Peak CS	0.58 <sup>b</sup>	NS
KinSco2	-0.58 <sup>b</sup>	NS

<sup>a</sup> ARMD, age-related macular degeneration; LCVA, low-contrast visual acuity; LogCS2.0, logarithm of contrast sensitivity at 2 cpd; LogCS4.0, logarithm of contrast sensitivity at 4 cpd; LogCS8.0, logarithm of contrast sensitivity at 8 cpd; PeakCS, logarithm of highest recorded contrast sensitivity from five spatial frequencies (0.5, 1.0, 2.0, 4.0, and 8.0 cpd); KinSco2, size of a binocular scotoma (steradians) as measured using a Humphrey Field Analyzer (IV 4E target); PPWS<sub>total</sub>, percentage preferred walking speed averaged over the entire mobility course; Contacts Score<sub>total</sub>, logarithmic transformation of total number of obstacles contacted over the entire course; NS, not significant.

<sup>b</sup> p < 0.01.

<sup>c</sup> p < 0.02.

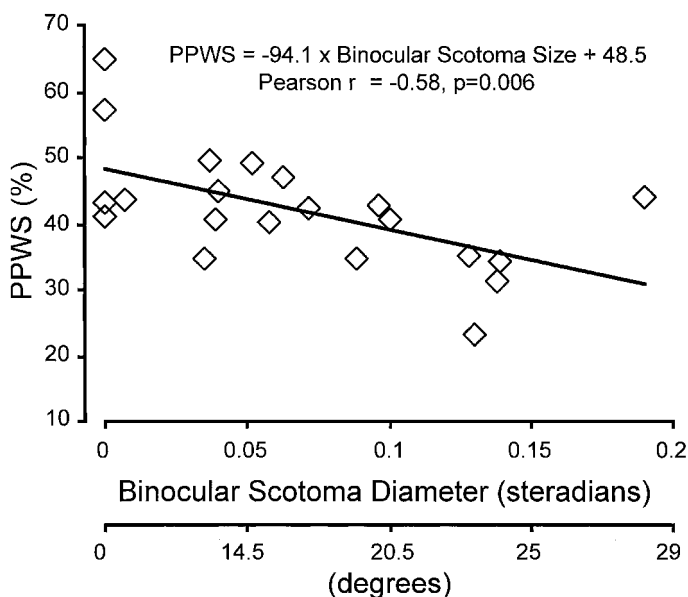


**FIGURE 2.** Variation in percentage preferred walking speed (PPWS) across four stages of the mobility course for the age-related macular degeneration (ARMD) and the control groups. Error Bars represent 1 SEM.

pared with normally sighted subjects of similar age. This was confirmed in both measures of mobility performance because the ARMD subjects did not significantly reduce their preferred walking speed on the obstacle course compared with the age-matched normally sighted subjects, nor did they make significantly more contacts with obstacles than did the normally sighted subjects.

PPWS of both the ARMD and normally sighted groups was significantly reduced under conditions of reduced illumination and glare (stage g) relative to their performance under high-illumination conditions. This most likely occurred because the task of walking through stage g was so difficult for both subject groups. Support for this suggestion is based on the finding that a younger group of normally sighted subjects (average age 45 years) when walking the same mobility course used in the current study also demonstrated significant reductions in their mobility performance in stage g compared with their performance in the high-illumination conditions of stages a and b.<sup>43</sup> Kuyk and Elliott<sup>15</sup> similarly found that reduced illumination resulted in significantly reduced walking speed and significantly increased number of mobility incidents for their ARMD group on their mobility courses.

Compared with the initial two stages of the course (stages a and b), both groups also demonstrated impaired PPWS in stage c, following the glare room. This result was unexpected because stage c was of similar illuminance to stages a and b. One explanation may relate to the subjects, inability to recover from the glare and to light adapt when emerging from the glare and reduced illumination of stage g into a brightly lit room (stage c). Glare recovery and light adaptation are often reported as serious problems among visually impaired people, including those with ARMD.<sup>44</sup> The other factor that may have contributed to reduced mobility performance in stage c was the time spent on task 2, especially after exposure to the light conditions of stage g.



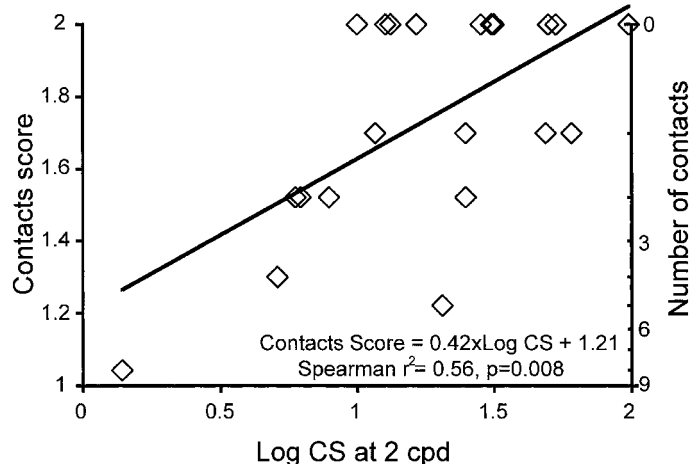
**FIGURE 3.**

Relationship between mobility performance scored as percentage preferred walking speed (PPWS) and size of binocular scotoma for age-related macular degeneration subjects. For ease of interpretation, in addition to the solid angle of the central scotoma (steradians), a second axis has been included showing the approximate diameter of the scotoma using the assumption that the scotoma was circular.

This may have increased subjects' times in stage c and hence lowered PPWS. Because task 2 was situated so close to the start of stage c and the time to complete this task was not recorded separately, it is not possible to say which factor, task 2 or light adaptation and glare recovery, contributed more to lowering PPWS for both subject groups.

In measuring the "safety" aspect of mobility using contacts score, we found that despite an obstacle-rich mobility course, subjects with ARMD did not contact more obstacles than did the normally sighted subjects. This indirectly agrees with Kuyk et al.<sup>17,45</sup> because their "acuity loss" group (comprising mainly ARMD subjects) made significantly fewer contacts than their "VF" and "combination" vision loss groups. Although neither of the Kuyk et al.<sup>17,45</sup> studies included normally sighted subjects, their results do indicate that subjects with ARMD make relatively few obstacle contacts. However, we acknowledge that number of obstacle contacts may be an insensitive mobility measure given the low frequencies (counts) of obstacle contacts in this and previous studies.<sup>16,18</sup> Other measures of the safety aspect of mobility performance need to be developed.

The luminance and height of obstacles did not affect the mobility performance of subjects with ARMD. Kuyk et al.<sup>45</sup> found a similar result for the effect of obstacle luminance, but not for the effect of height on the mobility performance of their acuity loss group. Kuyk et al.<sup>45</sup> reported that their acuity loss group contacted significantly more superior and step-over obstacles than floor-level walk-around obstacles. The step-over and superior obstacles used by Kuyk et al.<sup>45</sup> were approximately equivalent to our level 1 (inferiorly placed obstacles) and level 5 (superiorly placed) obstacles, whereas their floor-level walk-around obstacles were approximately equivalent to our level 2 and 3 obstacles (obstacles that ranged in height from the ankle to the waist). The discrepancy in results between studies may be because obstacle contacts in each height category were such a rare event for the ARMD group in the current study that differences in the number of contacts made between each obstacle height category were not significant.



**FIGURE 4.**

Relationship between mobility performance scored as contacts score and contrast sensitivity (CS) at 2 cpd for age-related macular degeneration subjects. For ease of interpretation, the axis on the right shows the actual number of obstacles contacted.

**TABLE 6.**Vision predictor variables of ARMD mobility performance from stepwise linear regression<sup>a</sup>

Regression Sequence	Vision Variables in Multiple Regression Analysis	Mobility Performance Measure	Vision Predictor Variables	Adjusted R <sup>2</sup>
1	Static VF measures	PPWS <sub>total</sub>	Static10 and Stasup30	0.29 <sup>b</sup>
2	Percentage remaining VF in seven zones	Contacts Score <sub>total</sub> PPWS <sub>total</sub>	None Zone 1 and Zone 2	— 0.29 <sup>b</sup>
3	Various VF measures	Contacts Score <sub>total</sub> PPWS <sub>total</sub>	Zone 1 Kinsco2	0.33 <sup>b</sup> 0.30 <sup>b</sup>
4	VA, contrast sensitivity, and selected VF measures	Contacts Score <sub>total</sub> PPWS <sub>total</sub>	Zone 1 KinSco2	0.33 <sup>b</sup> 0.30 <sup>b</sup>
		Contacts Score <sub>total</sub>	LogCS2.0	0.35 <sup>b</sup>

<sup>a</sup> ARMD, age-related macular degeneration; VF, visual field; VA, visual acuity; PPWS<sub>total</sub>, percentage preferred walking speed averaged over the entire mobility course; Contacts Score<sub>total</sub>, logarithmic transformation of total number of obstacles contacted over the entire mobility course; Static10, average static decibel sensitivity within central 10° radius VF; Stasup30, average static decibel sensitivity within superior 30° radius hemifield; zone 1, percentage remaining VF within the central 21° radius VF; zone 2, percentage remaining VF within the superior central 37° radius hemifield; KinSco2, size of a binocular scotoma (steradians) as measured using a Humphrey Field Analyzer (IV 4E target); LogCS2.0, logarithm contrast sensitivity at 2 cpd.

<sup>b</sup>  $p < 0.05$ .

### Predicting ARMD Mobility Performance from Vision Measures

Of the vision functions assessed, the size of a binocular scotoma and contrast sensitivity at 2.0 cpd were the best predictors of mobility performance in subjects with ARMD. This finding is in agreement with previous mobility research in which VF and contrast sensitivity measures have consistently been reported as the most important predictors of mobility performance.<sup>15, 16, 18, 23–25, 36, 46, 47</sup> However, this is the first time that the size of the central VF loss in ARMD has been shown to predict mobility performance. This finding indirectly supports the results of Turano et al.,<sup>48</sup> who found that postural stabilization (a prerequisite for efficient mobility) in subjects with and without ARMD was best predicted by the presence of a binocular scotoma within the central 5°. Turano et al.<sup>48</sup> found that the vision functions of VA and Pelli-Robson contrast sensitivity did not improve the power of prediction above the level obtained with a binocular scotoma.

Kuyk and Elliott,<sup>15</sup> for their obstacle course (the most similar of their three courses to ours), found that log contrast sensitivity was the most significant variable (in a four-variable regression model) to predict time taken to walk the course under photopic conditions by their ARMD subjects. VF extent was their most significant predictor of number of mobility incidents. Log contrast sensitivity was also the most significant predictor of both time and mobility incidents for their simpler courses. Kuyk and Elliott<sup>15</sup> suggested two possible reasons for their VF measure (VF extent) not emerging as frequently as log contrast sensitivity as a predictor of mobility performance in subjects with ARMD: either it is not as important to mobility in ARMD as it is to other groups (e.g., retinitis pigmentosa) or their measure of VF extent was not sensitive to mobility in subjects with ARMD. Because VF extent is not impaired in ARMD (except for normal reduction with age), it would not be expected to be associated with the mobility performance of

subjects with ARMD because of the limited range of VF extent scores. Our multiple regression analysis finding for PPWS<sub>total</sub> (fourth MRA, Table 6) indicates that a more detailed evaluation of the VF in ARMD, including an assessment of scotoma size, is important for predicting the mobility performance of subjects with ARMD.

As shown in Fig. 3, people with ARMD with no binocular scotoma reduce their speed when walking along an unfamiliar, complex indoor route to the same extent as normally sighted subjects of similar age. For example, we found that ARMD subjects with no binocular scotoma walked at approximately half their preferred walking speed, which was comparable to the average PPWS exhibited by our age-matched normally sighted subjects (46%). However, people with ARMD who have a binocular scotoma differ from normally sighted subjects of similar age in that they have reduced preferred walking speed on a complex route. From Fig. 3, people with ARMD with a binocular scotoma size of 0.1 steradians (equivalent to a scotoma of approximately 20° in diameter) are predicted to reduce their preferred walking speed by an additional 10% relative to people with ARMD with no binocular scotoma. The significant relationship between scotoma size and PPWS (fourth MRA in Table 6 and Fig. 3) suggests that at some point (i.e., with a large enough scotoma), mobility will become impaired. Therefore, for clinical purposes, we recommend that the binocular VF, including an assessment of scotoma size, be measured in ARMD patients to help predict their mobility performance.

As found in a number of previous studies,<sup>15, 23, 25</sup> we found that VA measures did not improve the prediction of mobility performance in the MRA models that included VF measures. The current study found no significant correlations between high-contrast VA and mobility. However, a significant correlation was found for the first time between low-contrast VA and PPWS<sub>total</sub>. Despite this, we found that mobility was more highly correlated with VF and contrast sensitivity measures than it was with VA. This finding

is in contrast to that of Brown et al.<sup>13</sup> who reported that VA, VF, and differential velocity discrimination accounted for 86% of the variance in mobility performance for subjects with ARMD. This discrepancy may relate to the small number of ARMD subjects assessed (N = 10), their use of a very simple mobility task that required only the detection of navigational poles (i.e., no obstacles), and the fact that Brown et al.<sup>13</sup> measured only those three vision functions: VA, VF (represented as inferior VF score and total VF score), and differential velocity discrimination at 20° and 30° eccentricities.

Unlike many real-world travel settings, the mobility course used in our study had no moving obstacles and had a well-defined path and set illuminance levels. Furthermore, stage g was not long enough to examine the different effects that reduced illumination and glare might have had on the mobility performances of the ARMD and normally sighted subjects. Despite these limitations, the controlled environment allows the determination of a more precise relationship between vision and mobility by removing confounding factors such as daily and seasonal changes in solar illumination and variations in mobility course complexity arising from varying numbers of dynamic obstacles such as pedestrians, animals, and vehicles. Kuyk et al.<sup>49</sup> reported that the results obtained from their laboratory controlled mobility course compared moderately well to the results obtained when they used a “real” outdoor mobility course.

The high density of static obstacles, particularly in the superior VF, might suggest that the lack of a difference in mobility performance between the ARMD and normally sighted groups was due to the complexity of the course, thereby leading to a floor effect. However, the same mobility course led to a significant difference in mobility performance (scored both as PPWS and contacts score) between subjects with retinitis pigmentosa and with normal vision of similar age.<sup>43</sup> This suggests that the mobility course was not inappropriately complex to detecting significant reductions in mobility performance between visually impaired and normally sighted subjects.

We found that vision variables were able to explain up to 35% of the variance in mobility performance in subjects with ARMD. The remaining variance is presumably explained by measurement errors in mobility and vision functions and from vision and sensory functions not assessed in this study. For example, the relationship between perceptual measures (higher-order vision functions) and mobility warrants further investigation, particularly because Kuyk et al.<sup>17</sup> and Kuyk and Elliott<sup>15</sup> found a perceptual test (i.e., scanning reaction time) emerged as a significant predictor of mobility performance using subjects with “acuity loss” and ARMD, respectively.

In summary, we found that the size of a binocular scotoma and contrast sensitivity at 2.0 cpd were important predictors of mobility performance in subjects with ARMD. Factors that affected the mobility performance of subjects with ARMD and with normal vision included the debilitating effects of reduced illumination and glare. The luminance and height of obstacles did not appear to have a significant effect on the likelihood of contacts by subjects with ARMD. The significant correlation found between binocular scotoma size and PPWS suggests that at some point (i.e., with a large enough scotoma), mobility will become impaired. For this reason, we recommend for clinical purposes that eye care practi-

tioners measure the size of any binocular scotoma in patients with ARMD to help predict when their mobility performance might decrease.

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