Effect of Bilateral Macular Scotomas from Age-Related Macular Degeneration on Reach-to-Grasp Hand Movement

George T. Timberlake,1,2 Evanthia Omoscharka,1 Barbara M. Quaney,1,3 Susan A. Grose,1 and Joseph H. Maino1

PURPOSE. Vision plays a critical role in reaching and grasping objects. Consequently, bilateral macular scotomas from age-related macular degeneration (AMD) may affect reach-to-grasp movements. The purpose of this work was to investigate changes in reach-to-grasp movement dynamics and to relate those changes to the characteristics of subjects’ preferred retinal loci (PRL), scotomas, and visual acuities.

METHODS. Three-dimensional positions of the index finger and thumb were recorded while subjects with bilateral scotomas and subjects with normal vision reached for and grasped blocks of three widths at two distances under binocular and monocular viewing conditions. Reach-dynamic parameters and the grip aperture (thumb-index finger distance) were calculated. Retinal locations and sizes of subjects’ scotomas and PRLs were mapped with a scanning laser ophthalmoscope.

RESULTS. Scotoma subjects’ hand trajectories had longer movement durations, lower maximum velocities, and longer visual reaction times than those of control subjects. With monocular viewing, maximum grip aperture (MGA) increased as a function of block width at a significantly higher rate for scotoma subjects than for control subjects. MGA decreased with increasing PRL bivariate normal ellipse area, and visual reaction time increased with decreasing acuity of the eye tested.

CONCLUSIONS. Compared with normally sighted subjects, subjects with bilateral macular scotomas from AMD have reach-to-grasp movements with longer trajectories, visual reaction times, lower velocities, and altered MGA-block width scaling. Visual reaction time and MGA are directly related to PRL characteristics. Deficits in reach-to-grasp movement caused by macular scotomas are greater in degree than those reported by others for real or artificial peripheral scotomas. (Invest Ophthalmol Vis Sci. 2011;52:2540–2550) DOI: 10.1167/iovs.10-6062

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Vision plays a crucial role in reaching and grasping objects.1–3 Before a reach-to-grasp movement begins, the visual system provides information to the brain about the size, shape, and location of the object to be grasped. The brain then uses the information to plan motor commands to move the hand toward the object. When the motor plan is activated, the hand accelerates toward the object in what has been referred to as the “transport” or “reach” movement phase. As the hand decelerates and approaches the object in the “grasp” movement phase, vision also provides information about the object and the posture of the hand preparing to grasp it.3–10

Given the important role of vision in prehensile movements, it is likely that central scotomas affect reach-to-grasp movement. Persons with bilateral macular scotomas usually adopt a unique peripheral retinal area adjacent to the scotomatus retinal area for inspecting the visual environment. This area, the preferred retinal locus (PRL),1,11,12 is a useful adaptation to central visual loss, but its function is poorer than that of the fovea. The PRL is most likely used to localize an object before reaching for it and to provide information about its size, shape, color, and texture. Macular scotomas may interfere with the process in several ways. First, more time to initiate a reach may be needed to place the target object image in the PRL, particularly if it initially falls in the scotoma. Second, the relatively poor visual resolution of a PRL as well as PRL fixation instability, may provide less than optimal information about object properties. Third, the scotoma may obscure the hand or object (or both) during reach-to-grasp movement. Finally, the lack of central binocular vision because of bilateral scotomas may reduce reach-to-grasp speed and accuracy.1,3–5,13–15

The effects on reach-to-grasp movements of both central16 and peripheral artificial scotomas7,16,17 and of scotomas from glaucoma18 have been reported. Sivak and MacKenzie16 investigated the effects on reach-to-grasp movements of artificial central scotomas in young subjects, but there have been no published investigations of the effects of central scotomas produced by disease or other disorders on reach-to-grasp movements. We investigated the effects of bilateral central scotomas in age-related macular degeneration (AMD) on reach-to-grasp movements. We also investigated the relationship between changes in reach-to-grasp movements and visual acuity and the characteristics of scotomas and PRLs found using the scanning laser ophthalmoscope (SLO).

METHODS

Subjects

Twenty subjects were tested, 10 with dense bilateral macular scotomas caused by AMD (scotoma group) and 10 with normal vision (control group). Ages and visual acuities of the subjects are shown in Table 1. The mean ages of the control and scotoma groups were not statistically

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different (t-test, *P* = 0.215). A physical therapist tested subjects for normal range of motion of the right arm and hand. Potential subjects were excluded if they took medications that could affect arm and hand movement, had a neurologic or musculoskeletal disorder that affected arm or hand motion, had insulin-dependent diabetes, or did not pass the Folstein Mini Mental test. All subjects were right-handed. Before testing, fixation was assessed using an SLO. None of the scotoma subjects had foveal fixation; all control subjects fixated foveally. The PRLs, scotomas, and probable position of the nonfunctional foveas were mapped using the SLO and previously described methods.\(^1^9\),\(^2^0\) The dominant eye was determined using the Dolman hole-in-card test.\(^2^1\) Binocular vision was assessed with the Titmus Fly Test\(^2^2\) (Stereo Optical Co., Chicago, IL). All the control subjects were able to see the stereoscopic images in the test; none of the scotoma subjects was able to do so. Visual acuity was measured with an illuminated ETDRS chart. Before testing, all subjects provided written informed consent using a consent document approved by the Kansas City Veterans Administration Medical Center Internal Review Board. The research reported here adhered to the tenets of the Declaration of Helsinki.

**Apparatus and Procedure**

Subjects sat at a table and placed the thumb and index fingertip on starting position markers at the edge of the table (Fig. 1A). Small infrared LEDs were attached to the ends of the thumb and index finger. Three-dimensional positions of the infrared LEDs were recorded with a digital motion analysis system (DMAS; Spica Technology Corporation, Kihei, HI). This system uses two high-resolution digital infrared cameras placed at approximately right angles to each other approximately 3 meters from the test area. The cameras imaged the calibrated three-dimensional testing volume indicated by the vertical rods in Figure 1. The system digitally recorded the three-dimensional coordinates of the infrared LEDs on the subject’s thumb and index fingertip at 120 Hz, with resolution of LED position < 0.5 mm.

Subjects wore their preferred optical correction beneath a head-mounted visor that occluded vision of the table and blocks until a trial began (Fig. 1A). Each subject reached for a wooden block placed either 20 or 40 cm from the subject’s hand along the subject’s midline, perpendicular to the subject. Three block sizes were used. All blocks were 3.8 cm high and of the same volume and weight, but they differed in length and width. Block widths (dimensions that were grasped) were 7.7, 5.5, and 3.6 cm. Blocks were painted white on top and black on the sides for high contrast; the blocks were placed on a light-colored table surface. The subject was instructed to reach and grasp the block as quickly and accurately as possible and to lift it slightly. When the experimenter pressed a switch, the computer began recording three-dimensional LED position data, and the visor flipped up (8 ms rise time) allowing the block to be seen (Fig. 1B). The trial ended, and the computer stopped data collection as soon as the block was lifted from the table surface. Subjects first performed 30 trials binocularly and then 30 trials with monocular vision using the dominant eye. The three sizes of block were each presented 5 times at the 20- and 40-cm distances in random order.

**Statistical Analysis**

Three-dimensional coordinate data were analyzed with a technical computing program (MatLab; MathWorks, Natick, MA) after smoothing with an *n* = 5 boxcar average. The following parameters of the reach-to-grasp trajectories were calculated:

### Table 1. Subjects’ Ages and Visual Acuities

<table>
<thead>
<tr>
<th>Scotoma Subjects</th>
<th>Control Subjects</th>
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<tbody>
<tr>
<td>Age (y)</td>
<td>Duration (y)</td>
</tr>
<tr>
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</tr>
<tr>
<td>78</td>
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<td>10</td>
</tr>
<tr>
<td>81.4</td>
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</table>

Column means are shown in bold in the bottom row. Shaded cells show tested dominant eye.

Duration, years since onset of AMD symptoms; RE, right eye; LE, left eye; BE, both eyes.
1. **Directness ratio**, the ratio of the actual trajectory length of the thumb divided by the shortest possible (straight line) distance between thumb starting and ending positions.

2. **Visual reaction time**, the time from first vision of the block (i.e., when the visor began to lift) until the hand began to move (Fig. 2).

3. **Movement duration**, the time from the start of hand movement until hand velocity was zero (Fig. 2).

4. **Maximum velocity** of the hand (Fig. 2).

5. **Time to maximum velocity**, the time from the start of hand movement until maximum hand velocity.

6. **Deceleration duration**, the time from maximum velocity until hand motion ceases.

Calculation of these parameters was based on the thumb infrared LED marker, which has been shown to parallel the wrist trajectory. In addition to the parameters listed, the grip aperture (distance between the index finger and the thumb) was calculated throughout the trajectory, and the maximum grip aperture (MGA) was determined, as was the time to MGA from the start of hand movement (Fig. 2).

Preliminary analysis of data for all subjects and conditions indicated that the data were not normally distributed (Shapiro-Wilk tests, $W = 0.308$, $P = 0.001$), and sample data pairs of scotoma and control subjects did not satisfy equal variance conditions. Consequently, the data were analyzed using the nonparametric Friedman repeated-measures ANOVA on ranks with Student-Newman-Keuls post hoc comparisons. The Student-Newman-Keuls post hoc test calculates a $q$ value that is then compared to a critical value found in a studentized range table. For the post hoc comparisons here, the critical value for $a = 0.05$, $df = 36$, and number of groups compared = 4 was $q_{0.05,36,4} = 3.85$. Values of $q$ that exceeded 3.85 indicated a statistically significant

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**FIGURE 2.** Plot of thumb velocity (left axis, solid line) and grip aperture (right axis, dashed line) versus time for one 40-cm reach trial of a control subject. The visor flipped up at 0 second, allowing vision of the block.

**FIGURE 3.** Binocular and monocular trajectories of a control subject (top plots) and a scotoma subject (bottom plots) for 40- and 20-cm reaches. Three-dimensional trajectories are shown as seen from above. Each plot shows trajectories of five reaches. Th, thumb trajectories; In, index finger trajectories.
difference, whereas those < 3.85 indicated no difference. The values of $q$ for each test are given to provide some indication as to the strength of a statistical difference or the lack of one. Since the Friedman repeated-measures ANOVA on ranks tests whether there are differences in the medians among groups, results are plotted as box plots that show the median, 25th, and 75th percentiles and error bars representing the 10% to 90% percentiles. Preliminary data analysis indicated that the reach-to-grasp parameters were not statistically significantly different for different block sizes. Therefore, the data were collapsed over block size for further analysis of these parameters.

**RESULTS**

**Trajectories**

Three-dimensional trajectories of a control subject and a scotoma subject are shown from above (i.e., in the horizontal X, Y plane) for both binocular and monocular 20- and 40-cm reaches (Fig. 3). In Figure 3, the left-right (Y) distance between the index finger and thumb increased as the hand moved forward and then began to close as the block was approached. Overall, the trajectories of the control and scotoma subject appear similar in shape.

**Trajectory Variability**

Trajectory spatial variability of control and scotoma subjects was compared by sampling the X, Y, Z thumb position of individual trajectories every 25 mm of forward movement. The mean and SD were calculated for each 25-mm sample position in the vertical (up-down, Z axis) and in the horizontal (left-right, Y axis) directions (Fig. 4). In Figure 4, for both the control and scotoma subject, SDs were small at the start of the trajectory, greatest near the middle of the trajectory, then grew smaller again as the hand approached the object. For statistical comparison of control and scotoma trajectories, an index of variability was calculated for each subject by summing separately the horizontal SDs and vertical SDs. The index was calculated separately for the 20-cm and 40-cm reaches. Because the index was not normally distributed (Shapiro-Wilk, $W = 0.672$, $P < 0.001$), statistical comparisons were carried out using repeated-measures ANOVA on ranks. Index of variability for the three block sizes were combined because preliminary repeated-measures ANOVA on ranks indicated that the index was not significantly different across block size. Control and scotoma subjects’ vertical and horizontal trajectory variability indices did not differ significantly for either binocular or monocular 20-cm or 40-cm reaches (Student-Newman-Keuls tests, $q = 2.236$, $P > 0.05$).

**Directness Ratio**

Control and scotoma subjects’ trajectories were also compared on the basis of directness ratio. The larger the directness ratio, the longer the thumb trajectory. Median directness ratios of control and scotoma subjects were not significantly different for either the 20-cm binocular reaches (Student-Newman-Keuls, $q = 0.447$, $P > 0.5$) or monocular reaches (Student-Newman-Keuls, $q = 3.130$, $P > 0.5$; Fig. 5). For 40-cm reaches, however, scotoma subjects had significantly higher median directness ratios than control subjects for both binocular (Student-Newman-Keuls, $q = 4.287$, $P < 0.5$) and monocular (Student-Newman-Keuls, $q = 3.862$, $P < 0.5$) viewing conditions.
This indicates that scotoma subjects tended to make relatively longer trajectories than control subjects when reaching for the blocks at 40 cm. Scotoma subjects' median directness ratios were 24% higher than control subjects' for 40-cm binocular reaches and 2% higher for monocular reaches. Control subjects' binocular and monocular directness ratios were not significantly different for the 20-cm reaches (Student-Newman-Keuls, \( q = 3.130, P > 0.05 \)) or the 40-cm reaches (Student-Newman-Keuls, \( q = 1.342, P > 0.05 \)) nor were those of scotoma subjects (20 cm: Student-Newman-Keuls, \( q = 3.674, P > 0.05 \); 40 cm: Student-Newman-Keuls, \( q = 2.685, P > 0.05 \)).

**Visual Reaction Time**

Scotoma subjects had significantly longer median visual reaction times than control subjects for 20-cm binocular reaches (Student-Newman-Keuls, \( q = 3.865, P < 0.05 \)) and monocular reaches (Student-Newman-Keuls, \( q = 5.814, P < 0.05 \)) and for 40-cm binocular reaches (Student-Newman-Keuls, \( q = 5.367, P < 0.05 \)) and monocular reaches (Student-Newman-Keuls, \( q = 4.427, P < 0.05 \); Fig. 6). Scotoma subjects' median visual reaction times were 24% to 32% longer than those of control subjects. Visual reaction times with monocular viewing were not significantly different from those with binocular viewing for scotoma subjects or control subjects or for either reach distance.

**Movement Duration**

Scotoma subjects had significantly longer median movement durations than control subjects for 20-cm binocular reaches (Student-Newman-Keuls, \( q = 4.654, P < 0.05 \)) and monocular reaches (Student-Newman-Keuls, \( q = 6.708, P < 0.05 \)) and for 40-cm binocular reaches (Student-Newman-Keuls, \( q = 5.144, P < 0.05 \)) and monocular reaches (Student-Newman-Keuls, \( q = 6.708, P < 0.05 \); Fig. 7). For 20-cm reaches, scotoma subjects' median movement durations were approximately 30% longer than control subjects. For 40-cm reaches, scotoma subjects median movement durations were 28% and 59% longer than control subjects for binocular and monocular reaches, respectively. Binocular and monocular movement durations were not significantly different for control subjects for either the 20-cm reaches (Student-Newman-Keuls, \( q = 0.447, P > 0.05 \)) or the 40-cm reaches (Student-Newman-Keuls, \( q = 0.894, P > 0.05 \)) or for the scotoma subjects' 20-cm reaches (Student-Newman-Keuls, \( q = 1.642, P > 0.05 \)) or 40-cm reaches (Student-Newman-Keuls, \( q = 1.789, P > 0.05 \)).

**Maximum Velocity**

Thumb velocity as a function of time is shown for a control subject's 40-cm reach in Figure 2. Velocity increased rapidly, reaching a maximum at approximately 31% of movement duration. The hand then decelerated as it approached and grasped the block. Control subjects had median maximum velocities significantly higher (20%–68%) than scotoma subjects for 20-cm binocular reaches (Student-Newman-Keuls, \( q = 6.369, P < 0.05 \)) and for 40-cm monocular reaches (Student-Newman-Keuls, \( q = 6.361, P < 0.05 \)) and for 40-cm binocular reaches (Student-Newman-Keuls, \( q = 5.389, P < 0.05 \)) and monocular reaches (Student-Newman-Keuls, \( q = 5.367, P < 0.05 \); Fig. 8). Monocular and binocular maximum velocities differed signifi-
For 40-cm reaches, scotoma subjects had deceleration times significantly later (Student-Newman-Keuls, maximum velocity 3% later than control subjects, not a significant difference, 0.05). For 40-cm binocular reaches, scotoma subjects reached maximum velocity significantly later (26%) than control subjects (Student-Newman-Keuls, maximum velocity significantly later than control objects). For 40-cm binocular reaches, scotoma subjects reached maximum velocity earlier than control subjects (Fig. 9). These differences, however, were not significant (repeated-measures ANOVA on ranks, \( \chi^2 = 3.240, P = 0.0356 \)). For 40-cm binocular reaches, scotoma subjects reached maximum velocity 15% later than control subjects for 20-cm binocular reaches and 6% later for monocular reaches (Student-Newman-Keuls, \( q = 0.010, P > 0.05 \)). For 40-cm binocular reaches, scotoma subjects reached maximum velocity significantly later (20%) than control subjects (Student-Newman-Keuls, \( q = 5.367, P < 0.05 \)).

**Deceleration Duration**

Deceleration duration, the time from maximum velocity to cessation of hand motion (see Fig. 2) is shown for all conditions in Figure 10. Deceleration durations were 54% longer for scotoma subjects’ binocular 20-cm reaches (Student-Newman-Keuls, \( q = 4.919, P < 0.05 \)) and 51% longer (Student-Newman-Keuls, \( q = 4.654, P < 0.05 \)) for their monocular 20-cm reaches. For 40-cm reaches, scotoma subjects had deceleration times 44% longer (Student-Newman-Keuls, \( q = 6.261, P < 0.05 \)) than control subjects for binocular reaches and 66% longer (Student-Newman-Keuls, \( q = 4.899, P < 0.05 \)) for monocular reaches.

**Maximum Grip Aperture Scaling**

Grip aperture increased after the beginning of hand movement and reached a maximum at approximately 64% of movement duration (Fig. 2). The MGA has been shown to increase linearly with object size. Figure 11 shows regression lines and 95% confidence intervals for MGA versus block width for control and scotoma subjects with binocular (Fig. 11A) and monocular (Fig. 11B) viewing. Because MGAs for the 20-cm reaches did not differ significantly from those of the 40-cm reaches (Student-Newman-Keuls tests, \( q = 0.038 - 5.515; P > 0.05 \)), the 20- and 40-cm reach MGAs were combined for each block size within binocular and monocular conditions. The slope of the MGA versus block width regression line indicates the increase in width of MGA per unit increase in width of the object. The slope is a unitless measure (mm/mm) referred to as the grip scale factor. For binocular viewing (Fig. 11A), control subjects’ grip scale factor was 0.34. This slope was almost identical with that of scotoma subjects (0.367), and there was almost complete overlap of the 95% confidence intervals. The grip scale factors of control and scotoma subjects did not differ significantly (two-tailed, \( t = 0.044, P = 0.966 \)), nor did the \( Y \)-intercepts (two-tailed, \( t = 0.333, P = 0.739 \)). Thus, for binocular reaches, control and scotoma subjects adjusted their MGA identically as block size changed. This was not the case for monocular reaches, as shown in Figure 11B. Monocular MGAs of scotoma subjects were larger overall than those of control subjects and increased more rapidly as a function of block width. Grip scale factors for scotoma and control subjects (0.296 and 0.177, respectively) were significantly different (two-tailed, \( t = 2.087, P = 0.037 \)). This scotoma subjects increased their MGA as a function of block width 1.7 (i.e., \((0.296)/(0.177)\)) times that of control subjects. Regression line \( Y \)-intercepts were not significantly different (two-tailed, \( t = 0.521, P = 0.602 \)).

**Time to MGA**

As with time to maximum velocity, described previously, longer visual reaction times for scotoma subjects may bias the time to MGA toward longer times. Consequently, the time to MGA was calculated from the start of hand movement. The
time required to reach MGA from the start of hand movement is shown in Figure 12 for 20- and 40-cm reaches. Time to MGA is shown for each block size, because the times to MGA were significantly different for different block sizes (Student-Newman-Keuls, q = 4.65–7.10, P < 0.05). In Figure 12, median times to MGA within each group (e.g., within the group of control subjects, 20-cm reaches and monocular viewing) are longest for the widest block (block 1, 77.4 mm) and shortest for the narrowest block (block 3, 36.4 mm). Median times to MGA were significantly longer for scotoma subjects than for control subjects for each block size. For example, within binocular 20-cm reaches, scotoma subjects had a longer median time to MGA for block 1 than control subjects had for block 1, a longer median time for block 2 than control subjects, and a longer median time for block 3. These differences were significant for all monocular and binocular 20-cm reaches (Student-Newman-Keuls, q = 5.14–8.22, P < 0.05) and all monocular and binocular 40-cm reaches (Student-Newman-Keuls, q = 5.14–7.84, P < 0.05). Overall, time to MGA of scotoma subjects increased 18% to 39% compared with control subjects with scotomas than for control subjects. Although reach-to-grasp dynamic parameters were generally not strongly correlated with PRL and scotoma characteristics, visual reaction time was found to be significantly correlated with visual acuity of the dominant eye used for the task (r = 0.614, t-test, P = 0.004; Fig. 14B). As visual acuity decreased (i.e., minimum angular resolution in min arc increased), visual reaction time increased.

**DISCUSSION**

The goal of the present study was to determine how bilateral macular scotomas affect reach-to-grasp hand movements and to relate reach-to-grasp changes to PRL and scotoma characteristics. Overall, hand trajectory length and precision were not greatly affected by bilateral scotomas. However, trajectory dynamics (e.g., visual reaction time, movement duration, maximum velocity) were uniformly poorer for subjects with scotomas than for control subjects. Although reach-to-grasp dynamic parameters were generally not strongly correlated with PRL and scotoma characteristics, visual reaction time was found to be significantly correlated with visual acuity (presumably PRL acuity), and MGA was correlated with decreasing PRL size. Detailed discussion of these results follows.

**Trajectories**

The trajectory variability index was not significantly different for control and scotoma subjects indicating that, despite reduced visual capacity from macular scotomas, scotoma subjects obtained sufficient visual information to execute trajectories toward the target with as little variability as control subjects. Although trajectory variability of scotoma subjects was the same as of control subjects, scotoma subjects did have larger directness ratios for binocular and monocular 40-cm reaches. This means that for the longer reaches, scotoma subjects moved their hand along a longer path toward the object than did control subjects. The reason for such longer trajectory...
ries is unclear but may result from moving the hand so it is not obscured by the scotoma when the PRL is viewing the block. Longer trajectories also may result from the longer deceleration times of scotoma subjects.

**Reach Dynamics**

The percentage increases or decreases in reach dynamics parameters relative to controls for artificial and real scotomas from previously published studies and the present study are summarized in Table 2.16–18,34 The range of percentage changes in reach parameters for peripheral and for central scotomas is given in the last two rows of Table 2. The increases or decreases in reach parameters found in the present study are generally in the same direction (i.e., positive or negative) as those found by others for peripheral scotomas and artificial central scotomas. However, the percentage changes produced by artificial16 or real (present study) central scotomas are generally larger than those from artificial16,34 or real peripheral scotomas18 (Table 2, last two rows). A single exception is the 82% increase in deceleration duration with artificial binocular peripheral scotomas found by Sivak and MacKenzie.16 During the deceleration phase, visual feedback is used to make final corrections as the hand approaches the object.17,34 More deceleration time may be needed for this correction with central scotomas than with peripheral scotomas (with the exception mentioned) because central scotomas may obscure the hand or object or both, making online changes more difficult. In summary, central scotomas generally appear to produce larger deficits in reach-to-grasp dynamics than do peripheral scotomas. This seems reasonable in view of the potential obscuration of the target object and hand by the scotoma and the difficulty of using a PRL to gather visual information.

In the present study, for both control and scotoma subjects, reach dynamic parameters with monocular viewing were not significantly different from those with binocular viewing with the exception of a significant difference in maximum velocity for control subjects’ 20-cm reaches (Fig. 8). Previous studies of young, visually normal subjects have reported that monocular viewing results in increased movement duration, decreased peak velocities,4,13–15,41 and increased time to maximum velocity.4,14,15,35 It is possible that the general lack of change in reach dynamics with monocular viewing is related to aging because subjects in the present study were considerably older (mean age, 79.9 years) than those in the previous studies cited (mean reported age, ∼26 years). The lack of a difference in binocular and monocular dynamics parameters for scotoma subjects is not surprising because these subjects usually

<table>
<thead>
<tr>
<th>Scotoma Type</th>
<th>Reach Component</th>
<th>Grasp Component</th>
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<tbody>
<tr>
<td></td>
<td>Reach Distance (cm)</td>
<td>Reaction Time</td>
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</table>

Increases and decreases for other studies were calculated from data or graphs provided in the references. All percentages were rounded to the nearest whole percentage. Percentages ≤1.0 were given the value 0. Sivak and MacKenzie16 data were based on means. Kotecha et al.18 and present study data were based on medians.

* Based on 30-cm distance and 4° field of view.
† Better eye.
‡ Present study.
§ 11° central view.
|| 23° central view.
strongly preferred using one eye and showed no evidence of binocular vision.

**Maximum Grip Aperture**

There are conflicting reports concerning the effects of peripheral and central scotomas on MGA (Table 2). For peripheral scotomas, two previous studies reported an increase in MGA for scotoma subjects relative to control subjects with binocular viewing, whereas another study found no change. With monocular viewing, one study reported increased MGA with scotomas, whereas another found no difference in MGA between scotoma and control subjects. For central scotomas, the present study found no significant difference between MGA for scotoma and control subjects with binocular viewing. In contrast, Sivak and MacKenzie using binocular, artificial central scotomas, found a 36% increase in MGA with binocular viewing. However, the subjects in the present study differed from those of Sivak and MacKenzie in several ways. First, the subjects were considerably older, and there is a documented effect of age on prehension. Second, the subjects' scotomas resulted from disease and were long term, providing time for visuomotor adaptation. Third, scotoma subjects had all developed unique PRLs, and it is not known whether the artificial scotoma subjects in the Sivak and MacKenzie study developed short-term PRLs. These factors may account for the large increase in MGA for binocular viewing found by Sivak and MacKenzie compared with the finding of no increase in the present study.

Scotoma subjects’ lack of an increase in binocular MGA relative to control subjects as well as only a modest increase relative to control subjects with monocular viewing is consistent with the hypothesis that long-term experience with macular scotomas results in more complete visuomotor adaptation for prehensile movements than do artificial, temporary macular scotomas. Part of this adaptation may be due to improvement over time in the ability to judge the size and position of objects to be grasped using PRLs. Experiments comparing judgments of object size by normally sighted and scotoma subjects would help to address this. The time course of the visuomotor adaptation to central scotomas is unknown, but it is possible that subjects improve in grasping accuracy with increasing experience. Longitudinal measurements of PRL reach-to-grasp movements from the onset of macular scotomas may be useful in understanding the adaptation process and, perhaps, in developing rehabilitation procedures.

Previous studies by others of young, visually normal subjects found increased, decreased, or no change in MGA with monocular viewing compared with binocular viewing. In the present study with monocular viewing, scotoma subjects’ MGAs increased relative to control subjects (Table 2). Scotoma subjects’ MGAs were not different from those of control subjects in binocular viewing. It is possible that the observed increased MGA with monocular viewing represents a “safety margin” (i.e., making the grip aperture larger than necessary to ensure grasping) such as that described when all visual feedback is eliminated during the reach.

The range of increases in time to MGA of subjects with central scotomas relative to control subjects for both binocular and monocular viewing was 18% to 64% compared with 2% to 28% for peripheral scotomas (Table 2). Central scotomas, therefore, generally resulted in longer times to reach MGA than did peripheral scotomas, suggesting that central scotomas interfere more with gathering initial information about object position than do peripheral scotomas. This is consistent with the finding that positional uncertainty increases markedly with eccentricity in near-retinal peripheres (2.5°–10°). Similar to the range of eccentricities of subjects’ PRLs, previous studies also reported decreased, increased, or no change in the time to MGA with monocular viewing, whereas the present work found increases relative to control subjects in the time to MGA for both monocular and binocular viewing (Fig. 12).

**Grip Scale Factor**

Grip scale factors (i.e., slopes of regression lines of MGA versus object size) are shown in Table 3 for the present work and for five previous studies by others. Binocular grip scale factors for control subjects in the present study are 25% to 60% lower than the scale factors found by others and 76% to 80% lower for monocular viewing (Table 3). Binocular grip scale factors of scotoma subjects are 20% to 58% lower than those found by others and 59% to 66% lower for monocular viewing. These differences in grip aperture scaling between subjects in the present work and in work by others may be due to age differences. The age range of subjects in work by others (Table 3) was 19 to 28 years compared with 70 to 91 years in the present study. A variety of hand functions decrease with age and it is possible that these changes produced the observed changes in grip aperture scaling.

The present study also found that grip scale factor decreased with monocular viewing for both control and scotoma subjects (Table 3). The relative decrease of monocular to binocular grip scale factor was 49% for control subjects and 19% for scotoma subjects (Fig. 11). Scotoma subjects may have a monocular grip scale factor that is larger than that of control subjects and close to their binocular scale factor because scotoma subjects primarily use their dominant eye in both monocular and binocular viewing. Given that the retinal lesions that cause central scotomas are rarely the same size, shape, and position in both eyes, PRLs in both eyes are usually located on different retinal areas compared with the fovea. As a result, there is no retinal correspondence of PRLs, and there may be little or no central binocular vision.

**Table 3. Slope of Regression Line Fit to MGA versus Object Width (mm/mm)**

<table>
<thead>
<tr>
<th>Authors</th>
<th>Subject Mean Age (y)</th>
<th>n</th>
<th>Object Width (cm)</th>
<th>Binocular Slope</th>
<th>Monocular Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goodale et al.29</td>
<td>—</td>
<td>1</td>
<td>2.5–5</td>
<td>0.460</td>
<td></td>
</tr>
<tr>
<td>Servos et al.15</td>
<td>22.6</td>
<td>9</td>
<td>2–5</td>
<td>0.756</td>
<td>0.892</td>
</tr>
<tr>
<td>Servos and Goodale1</td>
<td>23.5</td>
<td>8</td>
<td>2–5</td>
<td>0.878</td>
<td>0.721</td>
</tr>
<tr>
<td>Kudoh et al.33</td>
<td>19–28</td>
<td>12</td>
<td>2–8</td>
<td>0.855</td>
<td></td>
</tr>
<tr>
<td>Jakobson and Goodale30</td>
<td>25.3</td>
<td>15</td>
<td>2–5</td>
<td>0.664</td>
<td></td>
</tr>
<tr>
<td>Present study (controls)</td>
<td>78.3</td>
<td>10</td>
<td>3.4–7.7</td>
<td>0.345</td>
<td>0.177</td>
</tr>
<tr>
<td>Present study (scotoma)</td>
<td>81.4</td>
<td>10</td>
<td>3.4–7.7</td>
<td>0.367</td>
<td>0.296</td>
</tr>
</tbody>
</table>

Slopes from previous studies were determined from data or graphs in the reference.
Retinal Correlations

The present work demonstrates that some changes in reach-to-grasp dynamics and MGA are directly related to retinal and visual changes produced by AMD. MGA decreased as a function of increasing PRL bivariate area (i.e., decreasing fixation stability) for each of the three block widths (Fig. 1A), and visual reaction time increased with decreasing visual acuity (Fig. 1B). Longer visual reaction times with reduced acuity may be attributed to poor visual resolution resulting in uncertainty about object shape, width, or position.

The finding that MGA decreases with increasing PRL bivariate area is puzzling because, intuitively, one would think that greater target image movement associated with a larger PRL bivariate ellipse area would increase uncertainty about target size and, hence, a larger MGA would be used. It has been shown previously that PRL bivariate area is positively correlated with PRL eccentricity, so it is possible that increasing PRL eccentricity is correlated with underestimation of object size and smaller MGA. However, others have found that the MGA of normally sighted subjects increased with increasing target object eccentricity, although perceptual estimation of target size did not. There are marked differences in that study and the present study with scotoma subjects. First, in the other study, young visually normal subjects fixated (foveally) a stimulus while the target object was presented at an eccentric position. Consequently, it is reasonable to assume that the stability of the object image on the retina was typical of normal fixation (≤0.1 deg²), which is an order of magnitude, or more, smaller than for PRL fixation by scotoma subjects in the present study. Second, the eccentricities in the other study were 10° to 40°, larger than the 3° to 12° range of PRL eccentricities in the present study. Thus, differences in target object image stability and eccentricity may account for the different findings in the two studies. It may be informative to perform the MGA and perceived object size measurements described by Brown, Halpert, and Goodale with scotoma subjects and with normally sighted subjects at eccentricities similar to those of the scotoma subjects’ PRLs.

Another factor that may affect MGA size is metamorphopsia associated with macular scotomas. Pincushion metamorphopsia has been found with macular holes and perceived line shortening with homonymous paracentral scotomas. In these studies, the amount of distortion is related to eccentricity. With pincushion distortion, block width would be perceived as smaller than normal, possibly resulting in a smaller MGA. If perceptual distortion at the PRL increases with increasing PRL eccentricity, then a smaller MGA might be expected with more eccentric PRLs that also have larger bivariate ellipse areas. Measurement of perceptual distortion at the PRL would be useful in elucidating the role of distortion in setting the MGA. Finally, it is possible that the correlations of MGA and PRL bivariate ellipse area are spurious given the relatively small number of subjects. Further testing will help answer this question.

Reaching and grasping a solitary block is not representative of everyday reaching and grasping situations, but investigating it may provide some insight into problems faced by persons with bilateral macular scotomas. A more realistic reach-to-grasp situation might be one in which the target object is in an environment with multiple objects of different sizes, shapes, and positions. Such cluttered visual environments undoubtedly make reaching and grasping a target object more difficult, and it would be important to describe reach-to-grasp movements with such cluttered conditions. We believe that it will also be important to investigate further the relationship between deficits in eye-hand coordination and retinal functional geography (e.g., retinal position, size of the PRL, scotoma). Ultimately, documenting real-time scotoma obscurations of the hand and objects and establishing PRL location during eye-hand coordination could be useful in developing effective rehabilitation measures.

References

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