Depth Perception and Grasp in Central Field Loss

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PURPOSE. We set out to determine whether individuals with central field loss benefit from using two eyes to perform a grasping task. Specifically, we tested the hypothesis that this advantage is correlated with coarse stereopsis, in addition to binocular summation indices of visual acuity, contrast sensitivity, and binocular visual field.

METHODS. Sixteen participants with macular degeneration and nine age-matched controls placed pegs on a pegboard, while their eye and hand movements were recorded. Importantly, the pegboard was placed near eye height, to minimize the contribution of monocular cues to peg position. All participants performed this task binocularly and monocularly. Before the experiment, we performed microperimetry to determine the profile of field loss in each eye and the locations of eccentric fixation (if applicable). In addition, we measured both acuity and contrast sensitivity monocularly and binocularly, and stereopsis by using both a RanDot test and a custom stereo test.

RESULTS. Peg-placement time was significantly shorter and participants made significantly fewer errors with binocular than with monocular viewing in both the patient and control groups. Among participants with measurable stereopsis, binocular advantage in peg-placement time was significantly correlated with stereoacuity ($\rho = -0.78$; $P = 0.003$). In patients without measurable stereopsis, the binocular advantage was related significantly to the overlap in the scotoma between the two eyes ($\rho = -0.81$; $P = 0.032$).

CONCLUSIONS. The high correlation between grasp performance and stereoacuity indicates that coarse stereopsis may benefit tasks of daily living for individuals with central field loss.

Keywords: central field loss, stereopsis, binocular visual field

In healthy vision, the fovea plays a critical role in gathering high-resolution information from the visual scene. Central field loss (CFL) not only impairs high-acuity visual function, but also impairs binocular vision when the two eyes have very different acuities, contrast sensitivities, or scotoma profiles. Thus, any disease that differentially affects acuity and contrast sensitivity in the two eyes, or causes disparate patterns of field loss in central vision, can have a negative impact on depth perception.

Age-related macular degeneration (AMD) is one of the leading causes of CFL. It affects 6.5% of the population above the age of 40 years in the United States.[1] Treatments for slowing the progression of "wet" AMD are now available and are used widely. As a result of these treatments, patients with wet AMD are more likely to have reduced acuity with some foveal sparing, or a much smaller area of CFL (Fletcher DC, et al. *IOVS* 2008;49:ARVO E-Abstract 4102). The more common form of the disease is "dry" AMD, where the early stages of the disease are often associated with foveal sparing, but advanced stages may include central blind spots and scotomas as large as 15° to 20° wide that frequently affect both eyes.[2,3] When both eyes are involved, a scotoma may form in binocular central vision leading to difficulties with many tasks of daily living, with patients often unaware of the presence of the scotomas.[4] In most cases, when the central scotoma includes the fovea, patients adopt an eccentric preferred retinal locus (PRL) for fixation.[5]

Individuals with different patterns of CFL in both eyes often exhibit monocular PRLs that are not in binocularly corresponding locations.[6] This is probably because many important tasks of daily living such as reading, recognizing faces, and watching television can be accomplished monocularly.[7–9] However, depth information is important for everyday tasks that require eye–hand coordination and for navigation.[10] There can be serious consequences when individuals do not know where things are in space or when they knock over hot liquids because they cannot judge depth. In this study we examined the effect of binocular vision and depth perception on manual grasp.

Most assessments of binocular vision in the context of aging and central vision loss are in terms of binocular gain or loss—whether the two eyes are better than one. Previous studies have looked at both visual acuity and contrast sensitivity. Tarita-Nistor et al.[11] have compared binocular summation of visual acuity in individuals with AMD and age-matched controls. They have found similar levels of binocular summation in both populations. Two classic studies[12,13] have shown that in the case of AMD, the contrast sensitivity measured with both eyes is often worse than that of the better eye alone. Schneck et al.[14] have obtained the same result in an elderly population,

showing that large interocular differences in contrast sensitivity are significantly correlated with binocular loss.

Schneck et al.[15] have specifically measured stereopsis as a function of age and have shown significant declines in individuals older than 70 years. Importantly, they have shown that loss of stereopsis is correlated with loss of acuity and contrast sensitivity—those with normal acuity and contrast sensitivity do not show a decline of stereoacuity with age. Advanced macular degeneration results in CFL (as well as acuity and contrast sensitivity loss), which is rarely similar in the two eyes. Nevertheless, it is possible to have coarse stereopsis depending on whether there is intact retina in roughly corresponding points in the two eyes. Here, we looked at both individuals with AMD and age-matched controls to examine whether it is macular degeneration status or stereopsis status that determines the performance in eye–hand coordination tasks. Specifically, we examined a peg-placement task in which participants have to reach for and grasp a peg near the center of a pegboard and place it in its appropriate slot. Our hypothesis is that *the presence of coarse stereopsis will confer a benefit to the peg-placement task*.

The effect of field loss on grasp has been studied with both simulations of field loss and with actual CFL in patients with macular degeneration. Sivak and MacKenzie[16] have studied grasp with simulated central or peripheral vision loss. Participants view the display binocularly and are required to grasp a dowel. They have shown that CFL of 10° affects both grasp and movement toward the dowel, whereas loss of peripheral vision affects mainly the movement toward the dowel. Pardhan and coworkers[17] have examined grasp in patients with CFL under binocular viewing conditions. They have shown that patients take longer to grasp the object[17] and transport it to a specified location and make more placement errors, compared to controls.[18] Timberlake and coworkers[19] have compared grasp with monocular and binocular viewing in controls and individuals with CFL due to AMD. There is no significant difference in maximum grip aperture between controls and patients for binocular viewing, but individuals with field loss are slower overall and have larger grip apertures under monocular viewing. The difference between controls and patients with CFL is much more marked than in studies with simulated CFL.[16] However, a study of grasp in stereo-anomalous participants has reported no significant difference in grip aperture between monocular versus binocular viewing, in either the stereo-deficient or stereo-normal group.[20] However, other grasp parameters, such as time-to-grasp, are larger in stereo-deficient participants. Grasp studies in control participants have shown that, in general, the magnitude of the binocular benefit depends on the experimental paradigm, with the largest benefits occurring under conditions of uncertainty when the size and the distance of the object vary considerably within a block of trials.[21–24]

In our study we examined the effect of both field loss *and* the lack of stereopsis on an eye–hand coordination task. Observers performed a peg-placement task under binocular or monocular viewing. Importantly, the pegboard was just 10 cm below eye height, so that binocular depth cues were important in performing the task (Fig. 1). This is unlike other studies in which the task is done on a table where the items to be manipulated are viewed from above so that observers get a two-dimensional "plan" view of the layout. We measured various metrics of peg placement and determined whether these metrics improved with binocular relative to monocular viewing. Furthermore, we sought to determine how the binocular advantage in the peg-placement task was correlated with binocular measures such as acuity summation, contrast summation, stereoacuity, and the improvement in visual field from monocular to binocular viewing.

METHODS

Participants

Our study included 25 participants: 16 with maculopathy (8 female) and 9 age-matched controls (7 female). Only the data of 14 patients were included in the statistical analysis. One patient with CFL was excluded from our study because he was diagnosed with advancing glaucoma midway through the study. Another patient is listed in Table 1 (P3) but was not included because we were not able to complete testing for contrast and visual field. All CFL patients were referred to us by the low vision rehabilitation practice of D.C.F. at California Pacific Medical Center. Patients were contacted by phone and asked if they were interested in participating. If they agreed, they were sent a copy of the consent form, to review at their leisure. On the first visit, the experimenter went over the consent form with the participant and explained the nature of the study and possible consequences, before obtaining written consent. The protocols in the study were approved by the Institutional Review Board at The Smith-Kettlewell Eye Research Institute and conformed to the guidelines of the Declaration of Helsinki for the treatment of human subjects.

Vision, Cognitive Status, and Handedness Assessment

Participants first completed a Mini-Mental State Examination (MMSE) to evaluate cognitive status. All of our patients passed the MMSE. They also completed an Edinburgh Handedness Inventory to determine their dominant hand.[25] All but one of the participants were right-handed with a laterality quotient greater than 60. One control was ambidextrous with a laterality quotient of −40 and performed the grasp task with her left hand. All participants performed the experiment with their dominant hand. Visual testing was conducted with participants seated 40 cm from the test material.

We measured visual acuity by using the MN Read visual chart with each eye viewing monocularly, and with binocular viewing. To reduce familiarity effects, a different version of the chart was used for each condition (left eye, right eye, binocular). The smallest letter size, the time to read each size, and the pattern of errors were noted. The viewing distance was 40 cm, but patients were allowed to view the chart at a closer distance, if necessary. Reading acuity was computed in units of logMAR: Acuity $+ 1.4 - $ (Sentences $\times 0.1$) + (Errors $\times 0.01$) + $\log_{10}$(40/Actual Viewing Distance in cm). Contrast sensitivity was measured by using the Mars chart, both monocularly and binocularly. Table 1 reports monocular (better eye) and binocular measures of acuity and contrast sensitivity. Stereoacuity was measured by using the RanDot stereo test, and patients with measurable stereopsis were tested again in a custom pellicle system with a beam splitter that combined images from two separate monitors, placed at right angles. Vertical- and horizontal-polarizing filters in front of the monitors and polarizing glasses worn by the observer ensured that each eye received the images presented on only one of the monitors. The observer was presented with two concentric circles made up of random dots in a temporal two-interval forced-choice task and asked to judge in which interval (first or second) the outer circle appeared to be in front of the central circle. The inner circle had a radius of 6° and the outer annulus had inner and outer radii of 6.1° and 7.5°, respectively. The outer circle was presented in crossed disparity in one of five steps of disparity ranging from 2 to 12 minutes.

Microperimetry was performed monocularly on each eye by using the Optos Optical Coherence Tomograph/Scanning Laser Ophthalmoscope (OCT/SLO; Optos, Marlborough, MA, USA),
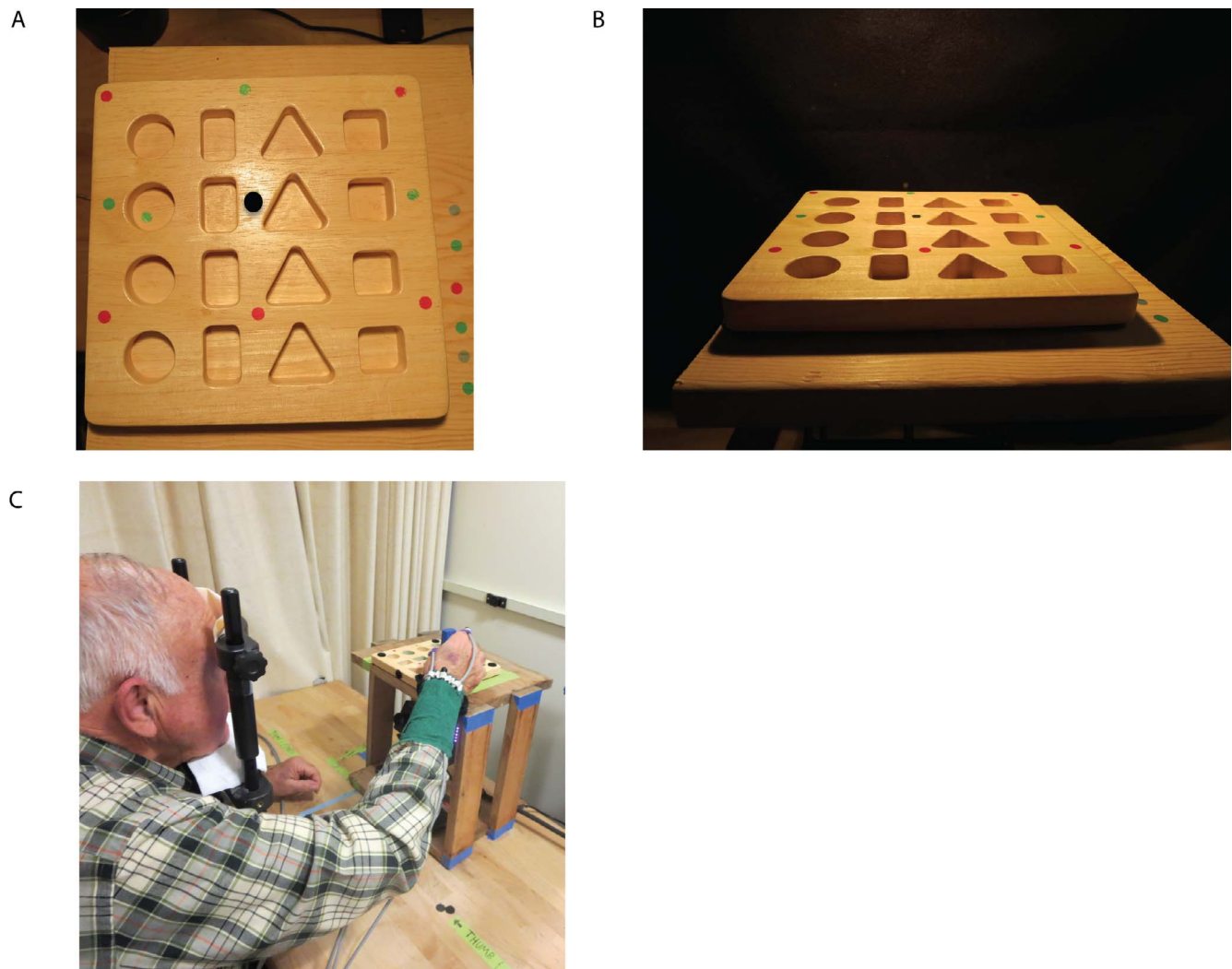
FIGURE 1. Pegboard setup. (**A**) Pegboard viewed from above. *Black dot* shows where peg is placed at the start of each trial. *Red* and *green dots* indicate calibration marks for the eye tracker. (**B**) Pegboard as seen by observer. The observer was seated so that eye position was 10 cm above the pegboard. (**C**) Participant reaching for the peg. The participant's head is in a chin and forehead rest. At the start of the trial, the participant lifts his hand from the table, picks up the peg and places it in the appropriate hole. Sensors on the thumb and index finger measure grasp and hand position in three dimensions. A table-mounted eye tracker placed under the pegboard measures binocular eye movements.

with a field size of 29.7°. A custom arrangement of points was used to determine scotoma profile. Fixation stability was also measured by using a 10-second fixation target and was characterized by a bivariate contour ellipse that include 68% of fixations.[26] The type of fixation target used was determined by self-reports of visibility from patients with field loss, and it included static or blinking white cross hairs, and static or blinking white dots. For controls we only used the static cross hairs. Each eye was tested monocularly while the other eye was occluded with a patch. Monocular scotoma mapping was performed by using microperimetry with unattenuated 0-dB dots (dot luminance, 125 cd/m²; Weber contrast, 12.5).

From each monocular microperimetry image (Figs. 2A and 2B) we used a method developed by Renninger et al. (Renninger LW, et al. *IOVS* 2008;49:ARVO E-Abstract 1508) and refined by Ghahghaei and Walker[27] to create a map of the scotoma in each eye in relation to the fovea. The scotoma map was developed by taking into account the increase in receptive field size with eccentricity from the fovea. When an OCT image is available and the foveal pit is intact, the location of the fovea can be measured directly. The location of the foveal pit estimated by the Optos

OCT/SLO is shown in Figure 2C for patient P8. If the foveal pit could not be visualized in both eyes owing to disease progression, the Ghahghaei-Walker[27] algorithm assumed that the fovea was symmetric in both eyes and used the location of the foveal pit from the center of the optic disc in one eye to estimate the location of the fovea in the other eye. In cases where the foveal pit could not be visualized in either eye (P1, P11), the algorithm estimated the distance of the fovea as 15° horizontally and 1.5° vertically from the center of the optic disc. This estimate is well within the range of estimates of other studies.[6,27] We used these maps to calculate the extent of the scotoma in each eye. We aligned the monocular maps on the estimated foveal locations in both eyes and calculated the area of scotoma overlap to determine the binocular scotoma (Fig. 2D).

Grasp Task

As we were interested in determining the benefit of depth perception, we used a peg-placement task with a novel arrangement of the pegboard (Geometric Peg Board 5125; Plan Toys, Plan Creations Co. Ltd., Bangkok, Thailand) with respect to the participant. Instead of placing the pegboard on a

Table 1. Participant Characteristics

ID	Age, y	Monocular Acuity, logMAR	Binocular Acuity, logMAR	Monocular CS, log	Binocular CS, log	Stereoacuity, arcmin	Monocular Scotoma Area, deg^2	Binocular Scotoma Area, deg^2
Patients								
P1	90	0.0969	0.0969	1.2	1.24	>30	128	60.6
P2	71	1	1.3	1.05	1.35	10	383	239.5
P3	85	0.961	0.602	–	–	–	–	–
P4	83	0.602	0.498	1.02	1.12	13.33	71	17.6
P5	86	0.204	0.0969	1.08	1.24	>30	531	132.8
P6	74	0.0969	0	1.60	1.68	5	30	0
P7	87	0.699	0.699	0.76	0.88	>30	160	29.1
P8	52	0.0969	0.0969	1.6	1.68	5	133.8	82.8
P9	90	1.38	1.146	0.64	1.04	>30	388	121.3
P10	70	0.0969	0.0969	1.8	1.32	>30	42.5	0
P11	76	0.602	0.602	1.24	1.24	>30	118	39.5
P12	72	0.602	0.602	1.4	1.44	>30	68.7	16.7
P13	78	0.301	0.301	1.36	1.40	3.67	38.3	0
P14	84	1.25	1.24	0.88	0.88	>30	378	350
P15	68	0.602	0.591	1.48	1.68	13.3	50.7	9.4
Controls								
C1	73	−0.0969	−0.0969	1.76	1.8	0.1	28.3	0
C2	74	0.204	0.0969	1.76	1.8	1	28.3	0
C3	76	0.204	0.0969	1.72	1.76	0.67	28.3	0
C4	65	–	−0.0969	1.64	1.76	3.3	28.3	0
C5	84	0	−0.0969	1.72	1.76	0.67	28.3	0
C6	76	0	0	1.76	1.8	>30	28.3	0
C7	52	−0.0969	−0.0969	1.8	1.8	0.67	28.3	0
C8	69	−0.0969	−0.0969	1.68	1.76	1	28.3	0
C9	71	0	0	1.72	1.8	0.67	28.3	0

Patients had age-related macular degeneration, except for P8 (Stargardt's disease), P12 (Best's disease), and P15 (ocular toxoplasmosis). For controls, the monocular scotoma is due to the optic disc. One patient (P2) and one control (C6) had a history of strabismus and had no measurable stereopsis. CS, contrast sensitivity.

table and affording observers a top-down view, we placed the pegboard just below eye height so that depth perception would help greatly in peg placement (Fig. 1). The pegboard was 30 cm above the table, at a distance of 40 cm from the observer. The observers' head was positioned so that their eyes were 10 cm above the pegboard. The pegboard had four rows, each with four unique shapes—circle, rectangle, triangle, and square. Observers were required to pick up a peg from a fixed position (Fig. 1, black dot; middle of the second row in the pegboard) and place it in the appropriate position in either the first or third row of the pegboard, as instructed by the experimenter. The first and third row had relative disparities of 15 and 17 arcminutes with respect to the starting position of the peg. Participants were seated with their chin and forehead resting in a head mount, which minimized head movement. Their grasping hand rested on the table at the start of the trial, with thumb and index (middle) finger resting on Velcro markers. Participants were given considerable practice with the task, until they were familiar with it. They were allowed to use either index or middle finger to grasp the block, depending on their preference. A Polhemus (Colchester, VT, USA) Liberty system sampling at 240 Hz was used to record three-dimensional movement data from sensors attached to the thumb, index (or middle) finger, and the wrist. Sensor position was measured with respect to a magnet placed under the table. Grip aperture was calculated as the distance between the thumb and index (middle) finger in three-dimensional space. Instantaneous hand velocity was computed as the average change in position of the thumb and finger sensor between consecutive frames. Hand velocity was smoothed with a temporal Gaussian filter with a temporal σ of 100 ms. Binocular

eye movements were recorded by an EyeLink 1000 Eye Tracker (SR Research, Ottawa, ON, Canada) in a table-mount configuration, angled to image both eyes of the participant. The red and green dots on the pegboard in Figures 1A and 1B are calibration marks for the eye tracker. Despite positioning the eye tracker optimally during a five-point calibration at the start of each block, the following combination of factors contributed to a loss of track of one or both eye during the block: eccentric eye gaze in patients, increased noise from the eye tracker due to the table-mount configuration, and patients potentially pitching their head slightly during the block.

Each block was made up of eight trials that required the four unique shapes to be placed in either the first or the third row. Before every trial, the experimenter informed the participant of the peg shape and the row in which it was to be placed. She then put the peg near the center of the board. Observers were asked to fixate a high-contrast marker on the bottom of each peg. When fixation was achieved, the trial began with a beep, which served as the go signal for the peg-placement task. Observers were asked to lift their hands from the Velcro markers on the table, pick up the peg, and place it in the appropriate position in the desired row (Fig. 1C). Hand movements were recorded from the time the hand reached a height of 15 cm above the table to just after the peg was placed. We compared monocular (M) and binocular (B) performance in separate blocks of trials. For patients with binocular CFL, monocular performance was measured while observers viewed with the better eye, with the worse eye occluded with an eye patch. For three patients (P6, P10, P13) with field loss in only one eye, monocular performance was measured with the affected eye. For controls, monocular
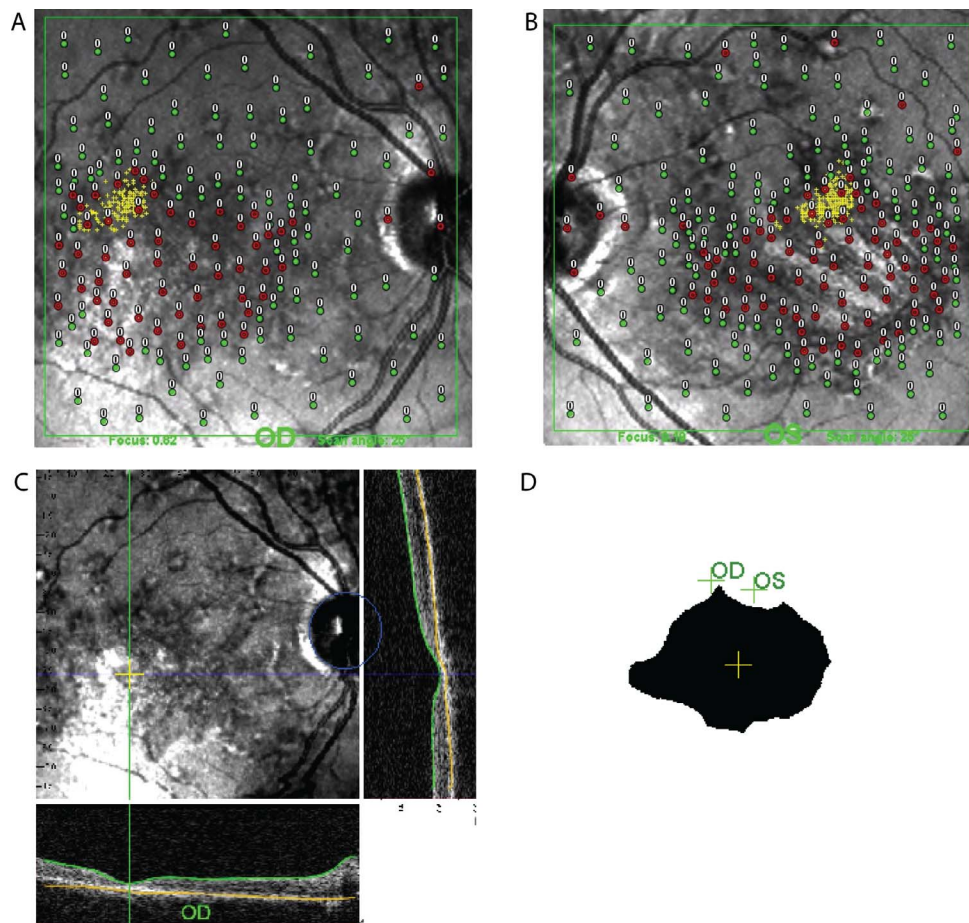
FIGURE 2. (**A**, **B**) Microperimetry for the right and left eye for P8. The *red* and *green dots* mark locations of unseen and seen flashes. The *yellow crosses* mark the fixation loci during perimetry. (**C**) Cross-sectional topography map allowing visualization of the foveal pit. (**D**) Binocular scotoma estimated by overlaying the two eyes' scotoma images, aligned on the fovea (*yellow cross*). The *green crosses* show the center of the bivariate contour ellipse of the fixation locus measured during a 10-second fixation assessment, for each eye separately (using the Ghahghaei and Walker[27] method).

viewing was with the dominant eye. Each observer took part in four blocks of trials and was randomly assigned MBBM or BMMB order. The four blocks were typically completed within the same session. The data in the first two blocks showed the same trend as the data in the last two blocks, except that they were noisy. To minimize learning effects we present only the last two blocks.

Dependent Variables

We used four measures of performance (the dependent variables in our study): pick-up time, peg-placement time, maximum grip aperture, and errors. The first two measures were defined from the profile of hand velocity over time (Fig. 3). We defined pick-up time as the interval between the point of maximum velocity to the point where velocity is minimum (when the hand slows to pick up the peg), and before velocity increases again as the hand is raised to place the peg. We defined peg-placement time from the point the peg is picked up to the point where the peg is placed, that is, from the time of minimum velocity around peg pick-up to the point of minimum velocity when the peg is placed. All estimates were based on analysis of individual trials. The points of maximum velocity, peg pick-up, and peg placement are shown in Figure 3A, with both the peg pick-up and peg-placement intervals marked. Figure 3A shows one observer's hand velocity for one trial under monocular viewing.

For comparison, Figure 3B shows hand velocity for the placement of the same block under both monocular and binocular conditions. Grip aperture was measured as the distance between the thumb and index (or middle) finger, and the maximum value of the grip aperture was recorded for every trial. To account for variations in finger size and placement of sensor on middle versus index finger, grip aperture values for a participant were normalized by that participant's grip size while their grip was closed on the circular peg. During the trial, the experimenter counted the errors made during peg placement. Any contact with the pegboard (including the rim of the peg hole) was counted as an error. Observers could have from 0 to 10 errors on each trial.

We compared binocular versus monocular performance for both patients and controls in our peg-placement task. On the basis of previous research on grasp,[19,20,24] we expected that binocular viewing would result in better performance (smaller grip aperture, shorter times to reach for and to place the peg, and fewer errors). Thus we performed within-subject comparisons to determine if binocular performance was indeed better than monocular performance. We also compared performance between subjects in the control and patient group to determine whether patient performance was worse than that of controls. Finally, because some of our patients have coarse stereopsis, we chose to partition participants by their stereo status rather than their macular degeneration status, to
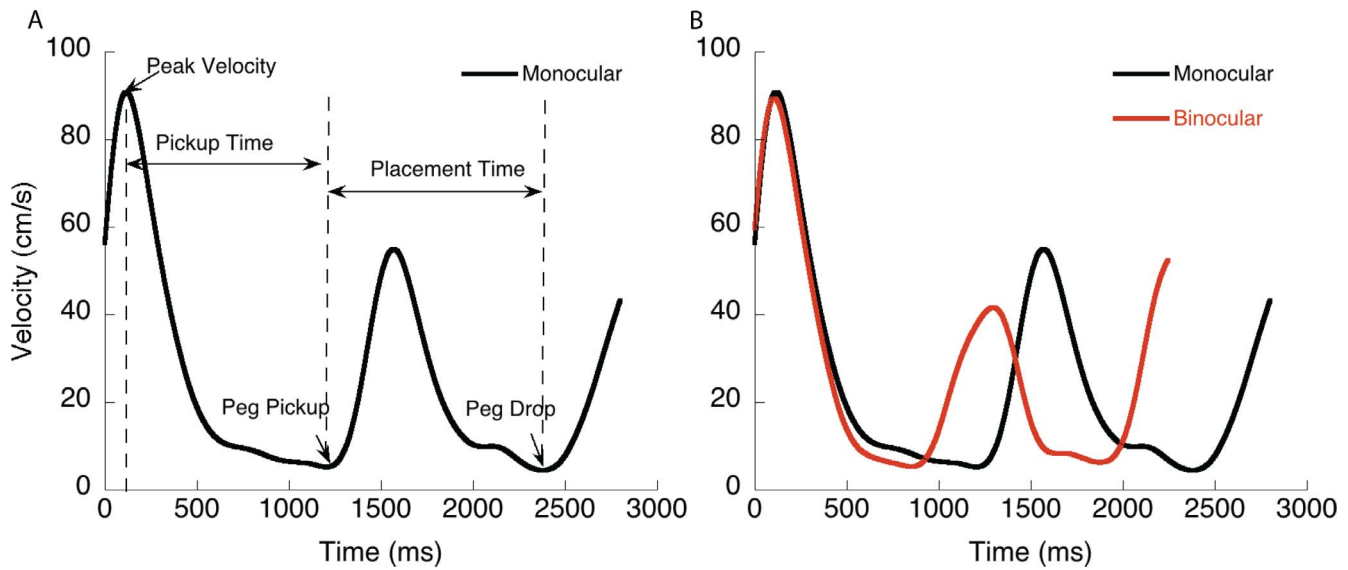
FIGURE 3. (**A**) Hand velocity data from one observer on a single trial as a function of time during peg placement. Peak velocity and the velocity minima associated with peg pick-up and peg drop-off are clearly marked. Pick-up time is the duration from peak velocity to peg pick-up, and peg placement time is the duration from peg pick-up to peg drop-off. (**B**) Comparison of hand velocity under monocular and binocular viewing conditions, while placing the same block in the same location.

determine whether coarse stereopsis conferred a benefit to peg placement.

Data Analysis

The data analysis consists of two parts. The first part compares aggregate data across groups (patients versus controls or stereo versus no-stereo), for each of the dependent variables, without taking into account independent variables such as acuity, contrast sensitivity, scotoma extent, and stereoacuity. The second part looks systematically at the dependence of performance on these independent variables, using a generalized linear model.

Data were averaged across eight monocular and binocular trials for each participant. Before we compared monocular and binocular performance for each of the dependent variables, we checked whether the values within a group (control, patient, stereo, no-stereo) were normally distributed by using the Shapiro-Wilk test. The distributions of either monocular or binocular values were often not normal, so we used the Wilcoxon signed rank test to compare binocular versus monocular performance of individuals within the group. To

compare performance across groups (either controls versus patients, or stereo versus no-stereo) we used an independent samples Mann-Whitney U test. Table 2 summarizes the results of these comparisons.

We also used a generalized linear model to determine how the independent variables (acuity summation, contrast summation, stereoacuity, and visual field gain with binocular viewing) influence the binocular benefit in the peg-placement task. Table 1 lists the characteristics of all our patients including binocular and monocular (better eye) acuity and contrast sensitivity, stereoacuity, scotoma area in each eye, and overlap of the scotoma. To characterize the benefit from binocular viewing we determined how the binocular benefit, which is the ratio of binocular to monocular performance in the independent variable (e.g., peg-placement time $PPT_{B/M}$), depends on binocular visual characteristics, such as binocular contrast and acuity summation, stereoacuity, and visual field improvement as defined below.

We ran generalized linear models that test whether there is an effect of binocular contrast summation (*ContrastSum*), binocular acuity summation (*AcuitySum*), binocular-to-monocular scotoma ratio (*VFRatio*), and stereoacuity on measures of task performance for our subject population as a whole, and whether there are separate interaction effects for (1) the subset of participants who have macular degeneration (indexed by an MD indicator, I_{MD}) and for (2) the subset of participants who do not have measurable stereo (indexed by a no-stereo indicator, I_{NS}). The model used an identity link function, based on the low kurtosis (<1) of the distribution of the values of the dependent variables.

The generalized linear model that classified participants as controls and macular degeneration patients is laid out in the following equations, using PPT as an example. But the equations apply equally to the other dependent variables:

$$
\begin{aligned}
PPT_{B/M} = {} & \alpha + \alpha_{CS}ContrastSum + \alpha_{VF}VFRatio \\
& + \alpha_{Acuity}AcuitySum + \alpha_{Stereo}Stereo \\
& + \alpha_{MD,CS}I_{MD}ContrastSum + \alpha_{MD,VF}I_{MD}VFRatio \\
& + \alpha_{MD,Acuity}I_{MD}AcuitySum,
\end{aligned} \tag{1}
$$

where

TABLE 2. Significance Levels of Statistical Tests (*P* Values)

	Binocular vs. Monocular		Controls vs. Patients	
	Controls	**Patients**	**Monocular**	**Binocular**
Grip aperture	*0.054*	*0.055*	0.124	0.159
Pick-up time	0.108	**0.008**	0.141	0.277
Placement time	**0.008**	**0.009**	**0.023**	**0.000**
Errors	**0.008**	**0.006**	*0.053*	**0.001**

Columns 1 and 2 show a within-subject comparison between monocular and binocular viewing conditions in controls (column 1) and patient (column 2) groups with the Wilcoxon signed rank test. Columns 3 and 4 show significance levels for a between-subject comparison (Mann-Whitney *U* test) of patients and controls for monocular and binocular viewing conditions. Values in bold are significant, values in italics are marginally significant.
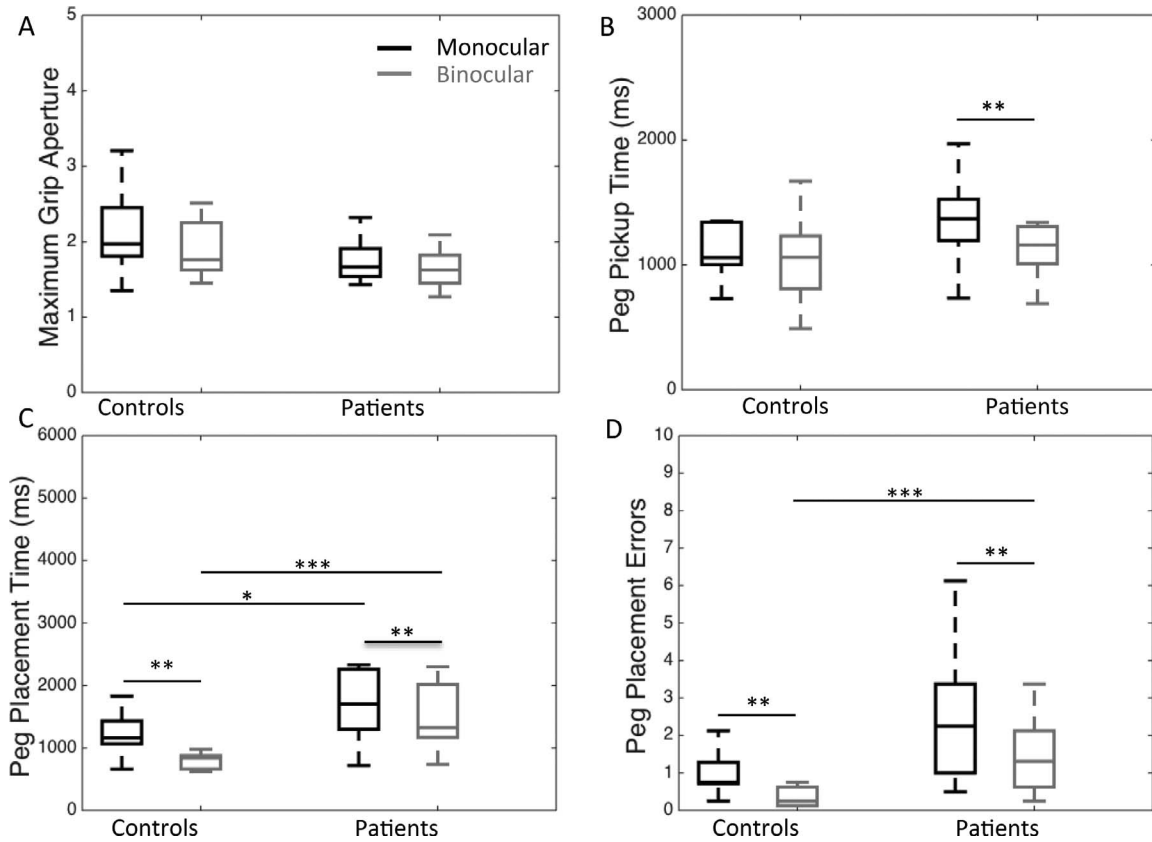
FIGURE 4. Average performance indices in the peg-placement task for controls and patients, under monocular (*black*) and binocular (*gray*) viewing conditions. (**A–D**) Maximum grip aperture, pick-up time, peg-placement time, and errors, respectively. The *line within the box* marks the median, and the *upper and lower bounds of the box* mark the upper and lower quartiles, respectively. The *whiskers* show the range of the data, excluding outliers (see text). Significance levels are marked with asterisks: *$P < 0.05$, **$P < 0.01$, ***$P < 0.005$ (see Table 2).

$$\text{PPT}_{B/M} = \frac{\text{PPT(Binocular)}}{\text{PPT(Monocular)}}$$

$$Stereo = \begin{cases} 0, & \text{No measurable stereoacuity} \\ \dfrac{1}{(Stereoacuity)}, & \text{else} \end{cases}$$

$$I_{\text{MD}} = \begin{cases} 1, & \text{Macular degeneration patient} \\ 0, & \text{else} \end{cases}$$

$$ContrastSum = \frac{ContrastSensitivity(\text{Binocular})}{ContrastSensitivity(\text{Monocular})}$$

$$AcuitySum = LogMARAcuity(\text{Binocular}) - LogMARAcuity(\text{Monocular})$$

$$VFRatio = \frac{ScotomaSize(\text{Binocular})}{ScotomaSize(\text{Monocular}) + \text{Optic Disc}}.$$

The α terms with subscripts are coefficients that weight the independent variables. Binocular contrast and acuity summation are defined as binocular sensitivity relative to better-eye sensitivity (Hu S, et al. *IOVS* 1994;35:ARVO Abstract 1527).[11–14,28] The scotoma ratio is the ratio of the estimated extent of the scotoma under binocular viewing to the extent of the scotoma measured monocularly. By this measure, controls have no binocular scotoma, as do patients with nonoverlapping scotomata in the two eyes. At the other extreme, a patient with completely overlapping scotomata in the two eyes has the same binocular and monocular scotoma and thus has a scotoma ratio equal to 1. Because controls have no binocular scotoma, their *VFRatio* is 0 (see Table 1), and therefore the contribution of the *VFRatio* term is the same with and without the interaction term, making the latter redundant.

A similar generalized linear model was set up to determine the effect of coarse stereopsis on grasp performance. In this case instead of an indicator for the presence of macular degeneration, we incorporated an indicator for no-stereo. The model is similar, except for the no-stereo interaction term I_{NS}, which is 1 for participants with no stereopsis, and 0 for those who have measurable stereopsis.

$$\begin{aligned} \text{PPT}_{B/M} = {} & \alpha + \alpha_{\text{CS}} ContrastSum + \alpha_{\text{VF}} VFRatio \\ & + \alpha_{\text{Acuity}} AcuitySum + \alpha_{\text{Stereo}} Stereo \\ & + \alpha_{\text{NS,CS}} I_{\text{NS}} ContrastSum + \alpha_{\text{NS,VF}} I_{\text{NS}} VFRatio \\ & + \alpha_{\text{NS,Acuity}} I_{\text{NS}} AcuitySum \end{aligned} \qquad (2)$$

RESULTS

We measured four characteristics of peg-placement performance, both binocularly and monocularly, for CFL patients and for controls. Maximum grip aperture normalized by closed grip on the circular peg, pick-up time, peg-placement time, and errors are plotted in Figures 4A, 4B, 4C, and 4D, respectively. Each panel shows four box and whisker plots: monocular (black) and binocular (gray) data for controls on the left and

TABLE 3. Comparison of Performance for Participants With and Without Stereo

	Binocular vs. Monocular		Stereo vs. None	
	Stereo	No-Stereo	Monocular	Binocular
Grip aperture	**0.019**	*0.214*	0.516	0.6
Pick-up time	0.055	**0.021**	0.688	1
Placement time	**0.006**	**0.011**	**0.003**	**0.007**
Errors	**0.006**	**0.008**	**0.028**	**0.005**

The format is similar to Table 2.

corresponding data for patients on the right. The horizontal line in the box marks the median, and the upper and lower bounds of the box mark the 75th and 25th quartiles, respectively. The whiskers mark the extreme values that are not outliers. (Outliers are points that exceed 1.5 times the interquartile range beyond the quartiles, equivalent to $\pm 2.7\sigma$ for a normal distribution). Outliers are relevant here only in relation to the placement of the whiskers. The statistical analysis included all points; the outliers were not excluded. As some of these distributions were not normally distributed, we used the nonparametric Wilcoxon signed rank test for within-subjects comparison. There was a significant benefit of binocular viewing for peg-placement time and errors, for both controls and patients (see Table 2, columns 1 and 2). There was a marginally significant reduction in grip aperture for both patients and controls. Only patients showed a significant binocular benefit in peg pick-up time.

In addition to comparing binocular versus monocular performance within a participant group, we also looked for differences in performance between patients and controls. There was no significant difference between patients and controls for either maximum grip aperture or peg pick-up time (between-subjects Mann-Whitney U test), for either monocular or binocular viewing (Table 2, columns 3 and 4, respectively). The lack of an effect for peg pick-up time is perhaps because the peg was always placed at the center of the board for every trial, and that with practice, grasping a peg at a known location was less dependent on the quality of vision in the central visual field. Only peg-placement time (the time from picking up the peg to putting it in the peg hole) was significantly different between controls and patients, with patients taking longer to place the peg under both monocular and binocular viewing conditions. Patients made more errors (unnecessary contact with the board) than controls; this was marginally significant under monocular viewing and significant under binocular viewing.

We also compared peg-placement performance among participants who had measurable stereopsis (regardless of their AMD status) and those who did not. A within-group comparison showed significant differences between monocular and binocular viewing for maximum grip aperture (stereo-group only; Fig. 5A), pick-up time (no-stereo group only; Fig. 5B), and for peg-placement time and errors (both stereo and no-stereo groups). Furthermore, a between-groups comparison showed significant differences for peg-placement time and errors under both monocular and binocular viewing conditions (Table 3, columns 3 and 4; Figs. 5C and 5D). Grip aperture and peg pick-up time were not significantly different.

One might expect that individuals with stereopsis will benefit considerably from binocular viewing. To determine whether this is true within our patient group, we compared performance of patients with and without stereopsis. When we compared the performance metrics most improved by binocular viewing in our experimental paradigm, namely, peg-

placement time and errors (Figs. 4, 5), performance was better for the stereo group ($n = 6$) than the no-stereo group ($n = 8$), but the difference was either not significant or only marginally significant, likely because of the small numbers in each subgroup. Under binocular viewing, the average peg-placement time was 1.29 ± 0.21 and 1.70 ± 0.40 seconds for the stereo and no-stereo groups, respectively. A Mann-Whitney U test showed that the difference in peg-placement time was not significant ($P > 0.05$). The average number of errors per trial was 1.71 ± 0.39 and 3.39 ± 0.87 for the stereo and no-stereo groups, respectively, which was marginally significant ($P = 0.07$).

Any comparison across or within groups is likely confounded by the large variability in the residual vision of our patient group. A more informative way to understand the data is to look at how performance in the grasp task varies as a function of the independent variables that characterize visual function, namely, binocular acuity and contrast summation, binocular field improvement and stereoacuity. To characterize the benefit from binocular viewing in patients and controls, we calculated the binocular-to-monocular performance ratio of the dependent variables. From our initial within-subject comparisons, only peg-placement time and errors showed a clear binocular benefit in patients and controls, so we sought to determine which combination of independent variables contributed to this effect. The generalized linear model determined the effect of binocular contrast summation, binocular acuity summation, binocular-to-monocular scotoma ratio, and stereoacuity (independent variables) on $PPT_{B/M}$, and on $Error_{B/M}$ for our subject population as a whole and whether there are separate interaction effects for the subset of participants who have macular degeneration (indexed by a macular degeneration indicator, I_{MD}). Table 1 lists the characteristics of all our patients, including binocular and monocular acuity and contrast sensitivity, stereoacuity, scotoma area in the tested eye, and estimated binocular scotoma area. All controls and three patients had no binocular scotoma. Of these three patients, two had measurable stereopsis (P6, P13) and one did not (P10). We ran a separate model for peg-placement time and for errors.

First we ran generalized linear models with a group indicator for the MD group (Equation 1). The model was run on data from 23 participants: 14 patients and 9 controls. The omnibus test for the $PPT_{B/M}$ model was not significant (likelihood ratio $\chi^2 = 10.39$; $df = 6$; $P = 0.11$), and neither was the model for $Error_{B/M}$ (likelihood ratio $\chi^2 = 9.25$; $df = 6$; $P = 0.16$). Furthermore, none of the independent variables on their own had a significant effect for either the $PPT_{B/M}$ or the $Error_{B/M}$ models. As an aside, generalized linear models for the binocular-to-monocular ratio of maximum grip aperture and pick-up time, with macular degeneration as an interaction factor, were also not significant.

Next, we ran the model with a group indicator for participants with no measurable stereopsis (NS group indicator; Equation 2). We had 14 participants with measurable stereopsis (8 controls and 6 patients) and 9 participants without measurable stereo (1 control and 8 macular degeneration patients.) We ran separate generalized linear models for $PPT_{B/M}$ and $Error_{B/M}$. The omnibus test for the $PPT_{B/M}$ model was significant (likelihood ratio $\chi^2 = 16.86$; $df = 6$; $P = 0.018$). However, the omnibus test for the $Error_{B/M}$ model was not significant (likelihood ratio $\chi^2 = 6.01$; $df = 7$; $P = 0.53$).

Because we defined the stereo variable as 1/stereoacuity, and those without measurable stereo were assigned a value of 0, these individuals were excluded in the stereo contribution to the full model, effectively partitioning the participants into a stereo and a no-stereo group. The model shows that the following model coefficients were significantly different from
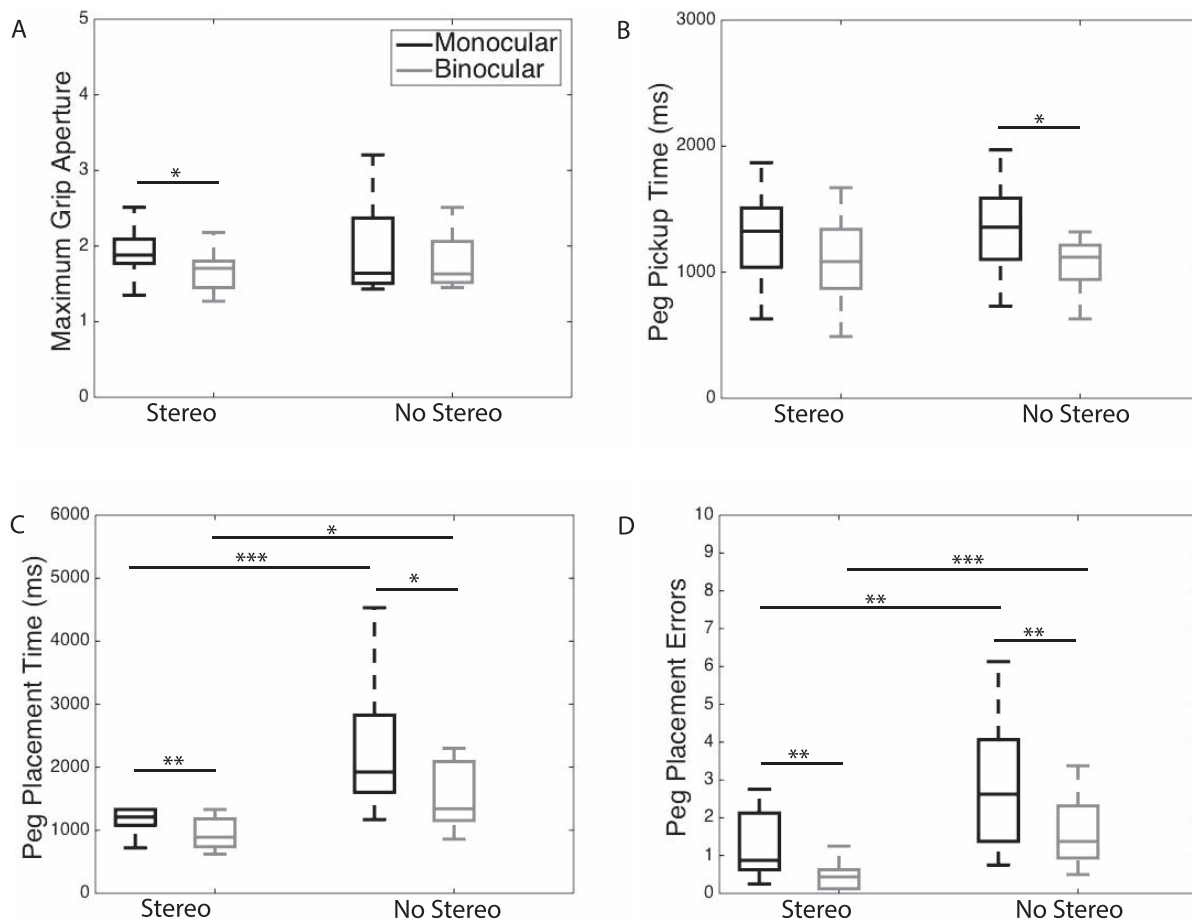
FIGURE 5. Average performance indices in the peg-placement task for participants with and without stereo, under monocular (*black*) and binocular (*gray*) viewing conditions. (**A–D**) Maximum grip aperture, pick-up time, peg-placement time, and errors, respectively. The *error bars* indicate the range of the data, excluding outliers. Significance levels are marked with asterisks: *$P < 0.05$, **$P < 0.01$, ***$P < 0.005$ (see Table 3).

zero ($P < 0.05$): α_{Stereo}, the coefficient for stereoacuity for those with measurable stereosis; and $\alpha_{NS, VF}$ the coefficient for visual field ratio, for those without. Thus, having measurable stereoacuity affected changes in PPT between binocular and monocular viewing conditions ($P = 0.003$). For those who did not have a measurable stereoacuity, scotoma ratio ($P = 0.034$) affected changes in PPT between binocular and monocular viewing conditions.

Because the model partitions the participants into two groups and only one independent variable is significant for each of these groups, we can look more closely at the effect of these significant variables on $PPT_{B/M}$. Stereoacuity was the only independent variable that was significantly correlated with the binocular-to-monocular ratio of peg-placement time for those with measurable stereo. This relationship is shown in Figure 6, which plots PPT ratio versus 1/stereoacuity for all participants (controls and patients) who had measurable stereopsis. It is clear that stereopsis was associated with binocular benefit in peg-placement time for both controls and for patients with macular degeneration. The patients are clustered on the left side of the graph, with poorer stereoacuity and smaller benefits from binocular viewing. We performed a nonparametric measure of association between the ratio of binocular to monocular peg-placement time, and the reciprocal of stereoacuity had a Spearman's $\rho = -0.78$, which is significant ($P < 0.01$).

The model also indicates that for the group with no measurable stereopsis, the binocular-to-monocular ratio of peg-placement time was significantly correlated (Spearman's $\rho =$

-0.81; $P < 0.05$) with the binocular-to-monocular scotoma ratio. This relation is plotted in Figure 7A for all patients without stereopsis. However, the correlation was in the opposite direction than predicted: peg placement takes less time under binocular viewing when the scotoma ratio is bigger, that is, when the binocular scotoma is more similar to the monocular scotoma, rather than when the binocular scotoma is small compared to the monocular scotoma. One possible explanation is that our estimation of the binocular scotoma may be incorrect. We assumed that the eyes were aligned, and we estimated the binocular scotoma by overlapping the monocular scotomas. But if the eyes are not aligned, the estimated binocular scotoma extent may be incorrect, especially for those who do not have stereo. However, it appears that our estimates of binocular scotoma extent are reasonable. Twelve of the 16 patients in this study had their binocular scotoma extent measured in another study in our laboratory, where the binocular scotoma was mapped by probing locations on a tangent screen while fixation was monitored with an eye tracker. Another possibility is that some patients with nonoverlapping scotomas (and thus a small binocular scotoma) have rivalry between the input from the two eyes, and thus do not benefit from binocular viewing. This may be similar to the transient blanking of the visual image for control participants when one eye (particularly the dominant eye) is patched.[29] Some of our patients complained of parts of the scene going blank periodically during binocular viewing. It appears that such rivalry decreases with progression of the
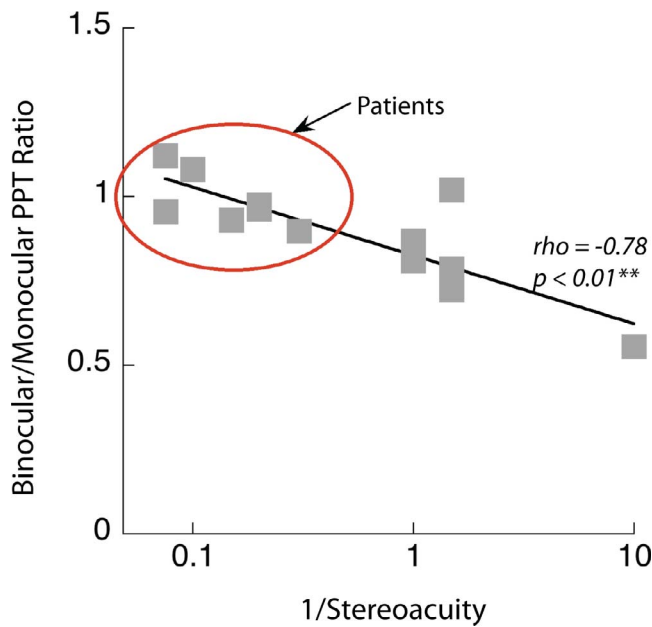
FIGURE 6. The binocular-to-monocular ratio of peg-placement time versus the reciprocal of stereoacuity. Patient data are marked with a *red circle*. Patients and control subjects have data that are well described by the same regression line.

disease[11] and may be less bothersome when the disease progresses, so that there is more overlap between the scotomata in the two eyes.

For completeness Figure 7B shows the relation between peg-placement time and binocular-to-monocular scotoma ratio in the subgroup of patients with stereo. The binocular benefit from peg placement appears to increase with ratio of binocular to monocular scotoma, but the correlation was not significant ($P > 0.05$).

DISCUSSION

We set out to measure the effect of CFL on eye–hand coordination tasks. In particular, we were interested in tasks

where depth perception was important, so we modified a peg-placement task so that binocular depth information would benefit task performance. We focused on four dependent variables of interest: maximum grip aperture, pick-up time, peg-placement time, and errors. In particular we were interested in how well the binocular benefit in peg-placement performance was explained by stereoacuity, and by binocular summation indices of acuity and contrast sensitivity, as well as field improvement from binocular viewing.

Our results showed no significant differences in maximum grip aperture among patients and controls (Fig. 4A), although each group showed a marginally significant decrease in grip aperture with binocular viewing. Similar to our results, Timberlake et al.[19] have found no difference in maximum grip aperture between patients and controls for binocular viewing, but have found that macular degeneration patients have a much larger grip aperture than controls for monocular viewing. This is perhaps because the blocks in the study of Timberlake et al.[19] have three different widths and were placed at one of two distances, whereas the pegs in our experiment were approximately the same size and were always placed at a distance of approximately 40 cm, so that patients may have quickly learned an appropriate grip aperture. This result is similar to that of a grasp study where there is no significant change between monocular and binocular viewing when the size and distance of the block is fixed.[23] Other studies that have varied both the distance and size of the block from trial to trial have typically found smaller grip apertures for binocular compared to monocular viewing.[21,23] However, in a separate study on the effect of stereopsis on grasp, Melmoth et al.[20] have found no significant difference in grip aperture under monocular (better eye) versus binocular viewing, between stereo-normal and stereo-deficient observers with strabismus. Thus, the effect of binocular versus monocular viewing on maximum grip aperture appears to depend both on the uncertainty in the distance and the size of the object to be grasped, and whether stereopsis is intact.

The fixed distance of the peg at the start of the trial might also explain why there was no significant difference in peg pick-up time between patients and controls. Only measures of peg-placement time and errors showed a significant difference between patients and controls, or equivalently, between participants with and without stereo. We discuss the effects
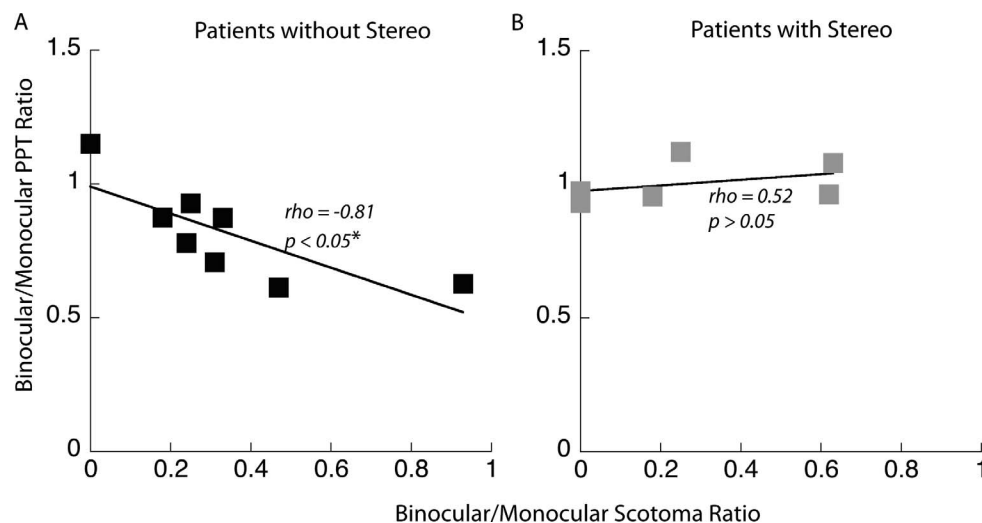

FIGURE 7. The binocular-to-monocular ratio of peg-placement time versus the binocular-to-monocular scotoma ratio for patients without stereo (**A**) and with stereo (**B**).

of our independent variables on these two metrics in more detail.

There was a significant difference in peg-placement time between patients and controls, similar to the results reported by Timmis and Pardhan,[18] and between individuals with and without measurable stereopsis. The generalized linear models showed that acuity summation (binocular-to-monocular ratio of visual acuity) is not a determinant of the binocular benefit in peg-placement time. This is true whether participants are grouped as controls and patients, or those with and without stereopsis. This finding is not surprising as the task did not require high resolution; it simply required using depth information to place relatively large pegs in corresponding holes on a pegboard. This is in contrast to other studies that suggest that binocular acuity summation (binocular-to-monocular acuity ratio) is a good indicator of how well the two eyes work together in patients with AMD.[11]

The generalized linear model also showed that the binocular-to-monocular ratio of contrast sensitivity was also not correlated with either peg-placement time or errors. A much smaller proportion of our patients (3 of 15) showed binocular contrast inhibition, compared to more than half the patients in the study of Faubert and Overbury.[12] This is perhaps because of difference in contrast sensitivity measures: we measured contrast sensitivity at the peak of the contrast sensitivity function with the Mars test, whereas Faubert and Overbury[12] have measured contrast sensitivity over a range of spatial frequencies and compared the area under the CSF under binocular and monocular viewing conditions.

Visual field improvement in individuals without measurable stereo (mostly patients) from binocular to monocular viewing was significantly correlated with the binocular benefit in peg-placement time ($P = 0.032$). The correlation showed that peg placement is better when the ratio of binocular to monocular visual field is close to 1. There appears to be little binocular benefit to peg placement for the smallest binocular-to-monocular field ratio, which occurs when there is little overlap between the scotoma in the two eyes (points on the left of Fig. 6). It is possible that patients with nonoverlapping scotomas experience rivalry between the two eyes' images, and therefore do not benefit as much from binocular viewing as patients who have more overlap between their scotoma, including those who have no field benefit from binocular viewing (right side of the graph). One concern in interpreting the binocular scotoma is the assumption inherent in our estimation of binocular field overlap. We assumed that the eyes of AMD patients were roughly aligned during binocular viewing, from the studies of Kabanarou et al.[6] These authors have measured the shift in gaze direction from monocular to binocular viewing and compared it to the distance between the monocular PRLs. They find that 27 of 29 participants have monocular PRLs in noncorresponding locations (average distance between PRLs: $7° \pm 5°$). They have found a strong correlation between the magnitude of the shift in gaze direction of the weaker eye and the distance between the monocular PRLs. Most participants display negligible shifts in the position of the stronger eye. Their data suggest that the convergence system is largely intact and that when both eyes are open, the input to the better eye drives convergence and the weaker eye is brought into alignment, perhaps at the cost of placing fixation within the scotoma. Thus, the assumption that the foveas in the two eyes are aligned during binocular viewing seems reasonable.

When we consider only those individuals with measurable stereopsis, peg-placement time was significantly correlated with stereoacuity in the stereo group ($P < 0.003$).

Furthermore, AMD patients who have coarse stereo had peg-placement times that fall on the same correlation line as age-matched controls (Fig. 5). As we saw earlier, contrast summation between the eyes was not correlated with performance in the peg-placement task. One would expect that if stereoacuity had a significant effect on peg placement, then interocular differences in contrast sensitivity would affect peg placement because they affect disparity thresholds. When equal contrasts are presented to each eye, disparity thresholds for depth judgments are inversely related to the square root of contrast. But when the contrast in one eye is lowered, disparity thresholds increase, compared to when the contrast of both eyes is lowered.[30,31] Even though stereoacuity is affected adversely by unequal contrasts in the two eyes, the individual can still have functional stereopsis despite an imbalance between the eyes. Most tasks of daily living do not require fine stereoacuity ($\sim$10 arcseconds) but benefit from stereopsis in the range of 1 to 10 arcminutes ($\sim$1 arcminute for detecting a depth of 1 mm at arms length and approximately 10 arcminutes to detect the drop-off at a curb). The disparity between the front and back of the peg hole ranged from 9 to 13 arcminutes depending on the shape, indicating that coarse stereopsis was sufficient for this task.

In fact one of our patients with fairly eccentric PRLs ($>12°$) had coarse stereoacuity of 10 arcminutes. Thus, eccentric fixation by itself does not compromise the potential for coarse binocular depth perception, as long as there is intact visual function in roughly corresponding points in the two eyes. Moreover, the peripheral retina can indeed support the stereoacuity required for most eye–hand coordination tasks. Disparity thresholds at an eccentricity of 10° can be as good as 2 arcminutes,[32,33] which is sufficient to judge a depth of approximately 1 mm at a distance of 40 cm.

The potential for coarse stereopsis to benefit patients with CFL with their daily activities has received little attention so far. One exception is the study by Cao and Markowitz[34] in which the authors measure stereoacuity in patients with AMD and also have them fill out the visual function questionnaire (VA LV VFQ-48). Patients with residual stereopsis report better visual function and mobility skills. This result, in combination with our study that showed the benefit of coarse stereopsis for eye–hand coordination for near work, suggests that coarse stereopsis can benefit the performance of everyday tasks in a three-dimensional world.

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