

# A Comparison of Reach-to-Grasp and Transport-to-Place Performance in Participants With Age-Related Macular Degeneration and Glaucoma

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**PURPOSE.** To compare visually guided manual prehension in participants with primarily central field loss (CFL) due to age-related macular degeneration and peripheral visual field loss (PFL) due to glaucoma. This study extends current literature by comparing directly “reach-to-grasp” performance, and presents a new task of “transport-to-place” the object accurately to a new location. Data were compared to age-matched controls.

**METHODS.** Three-dimensional motion data were collected from 17 glaucoma participants with PFL, 17 participants with age-related macular degeneration CFL and 10 age-matched control participants. Participants reached toward and grasped a cylindrical object (reach-to-grasp), and then transported and placed (transport-to-place) it at a different (predefined) peripheral location. Various kinematic indices were measured. Correlation analyses explored relationships between visual function and kinematic data.

**RESULTS.** In the reach-to-grasp phase, CFL patients exhibited significantly longer movement and reaction times when compared to PFL participants and controls. Central field loss participants also took longer to complete the movement and made more online movements in the latter part of the reach. During the transport-to-place phase, CFL participants showed increased deceleration times, longer movement trajectory, and increased vertical wrist displacement. Central field loss also showed higher errors in placing the object at a predefined location. A number of kinematic indices correlated significantly to central visual function indices ( $P < 0.05$ ).

**CONCLUSIONS.** Significant differences in performance exist between CFL and PFL participants. Various indices correlated significantly with loss in acuity and contrast sensitivity (CS), suggesting that performance is more dependent on central visual function irrespective of underlying pathology.

**Keywords:** glaucoma, AMD, reach-to-grasp

The prevalence of age-related macular degeneration (AMD) and glaucoma have increased by 100% and 160%, respectively, in the past 10 years and are projected to increase in the years to come.<sup>1</sup> Age-related macular degeneration typically affects the central field (CFL), while glaucoma normally begins with peripheral field loss (PFL). However, the progression of both diseases can lead to more extensive visual field loss, which may also include CFLs in glaucoma patients.

It is already known that vision plays an important role in planning and executing tasks requiring manual prehension such as reaching and grasping.<sup>2–4</sup> Reduced reach-to-grasp performance has been shown in normal subjects in whom central and PFLs have been simulated,<sup>5–8</sup> patients with AMD who have CFL,<sup>9–14</sup> and those with glaucoma with typical PFL deficits.<sup>15</sup> Timberlake et al.<sup>9</sup> examined the effect of bilateral macular scotomas on reach-to-grasp performance and showed longer movement durations, lower maximum velocities, and longer visual reaction times than those of control subjects. Research from our own laboratory has shown how various

parameters, including the duration of impairment, target contrast, and crowding of the objects influence reach-to-grasp performance in participants with AMD who have CFL deficits.<sup>10–14</sup> Kotecha et al.<sup>15</sup> suggested a decreased reach-to-grasp performance in patients suffering from glaucoma (PFL). Due to different methodologies, instruments, and procedures involved in these individual studies that investigated either CFL or PFL, it is difficult to directly compare the reach-to-grasp performance of participants with CFL versus those with PFL. Hence, very little is known as to how vision guided manual prehension performance compares between participants who have CFL and PFL. A previous study compared reaching and grasping performance on simulated CFL and PFL in young participants.<sup>7</sup> This study used a specially designed contact lens system to restrict information to the peripheral retina, and modified goggles to restrict information to the central retina. They reported that, with peripheral vision only (CFL), information related to size and shape of an object was inadequate, which affected both the transport and grasp



components. When only central vision was permitted (loss of peripheral vision) information related to the location of an object was inadequate, which affected the organization of the transport but not the grasp component. These findings, although important, have limited clinical implications when drawing inferences about a visually impaired population as they do not account for long-term visuomotor adaptation to vision loss<sup>11</sup> or the effects of age on manual prehension.<sup>16</sup>

In everyday life we perform a variety of other manual prehension tasks that extend beyond just reaching out and grasping an object. Once an object has been picked up, it is often necessary to transport it to another location and place it there. Self-report studies on AMD and glaucoma participants suggest an element of difficulty for tasks that require both reach-to-grasp and transport-to-place components. These tasks include setting the table,<sup>17-18</sup> putting away groceries,<sup>17</sup> and organizing objects.<sup>19</sup> Previous work from our laboratory, using objective assessments, showed that transport-to-place performance is impaired in participants with CFL.<sup>10</sup> We demonstrated that, when tasked with repositioning an object to another lateral location, patients with CFL took longer to complete the movement and had reduced online control, as suggested by an increased deceleration time and an increased number of velocity corrections when placing the object. Central field loss participants also exhibited greater errors than controls when placing the object at the end location. To date, an objective assessment of this task in participants with PFL has not been reported nor has a direct comparison with CFL participants been carried out. The transport-to-place task potentially extends the area of the visual field required to carry out the task compared to the traditional reach-and-grasp task. This may prove to be important for participants with PFL who may well experience increased difficulty in completing such a task, particularly if the final position of the object is in a more peripheral area of the visual field. As participants are required to reach out and pick up the object and then to locate the final position for the object through a visual search, there is arguably a greater visual demand placed on the participants when compared to the reach-to-grasp task. This also reflects a more realistic task found in daily living.

Using a three-dimensional motion analysis system, the aim of the study is to examine kinematic indices for transport-to-place that have not been examined before in participants with PFL. It also extends previous work<sup>2,15</sup> by comparing directly the performance of both reach-to-grasp and transport-to-place in patients with CFL and PFL. It will ascertain whether any decreases in performance are specific to the different ocular disease etiologies.

The direct aims of this study are to:

1. Compare directly reach-to-grasp performance in participants with AMD (primarily with CFL) and glaucoma (primarily with PFL) using the same methodology and equipment.
2. Examine how participants with PFL complete the transport-to-place of the object accurately to a different (predefined) location.
3. Examine whether any observed differences are associated with central or peripheral visual function (VF) loss.

## METHODS

### Participants

Seventeen participants with PFL (age  $74 \pm 8$  years), 17 participants with central visual impairment (age  $77.7 \pm 7$  years), and 10 control participants with normal vision (age 75

$\pm 6$  years) took part in the study. The mean ages of participants in each group were not significantly different between groups ( $P = 0.11$ ). Prior to data collection, health and physical fitness of all participants were assessed through a self-report questionnaire used previously.<sup>10</sup> Exclusion criteria included any history of neurologic or musculoskeletal disorders that could affect prehension performance, insulin-dependent diabetes, failure to pass the Mini Mental State Examination,<sup>20</sup> significant lens opacities, cataract surgery in the last year, or any history of other ocular conditions. Participants were excluded from the study if they had amblyopia or strabismus or if their motility (which extended to all directions of gaze) was not considered normal or was decompensated. Hand function was also assessed by a human movement scientist,<sup>21</sup> and each participant was deemed to have normal range of motion. An additional assessment of manual dexterity using the ABILHAND questionnaire was also completed.<sup>22</sup> An ocular examination of all participants was provided by a consultant ophthalmologist (RB). All 17 participants with CFL had been diagnosed with bilateral AMD. All participants with PFL had a diagnosis of bilateral primary open angle glaucoma (POAG). Ethical approval was obtained for the study from both Hinchingsbrooke Hospital Department of Research Governance and Anglia Ruskin University's Ethical Committee. The Tenets of the Declaration of Helsinki were observed. Written informed consent was obtained from each participant prior to undertaking the study.

### Visual Assessments

Binocular distance visual acuity (VA) was measured using a Bailey-Lovie logMAR chart at a working distance of 4 m, using a letter-by-letter scoring system. If participants were unable to read the largest letters on the logMAR chart at 4 m, shorter distances were used and the score adjusted accordingly. The Pelli-Robson chart was used to assess contrast sensitivity (CS) and stereopsis was measured using the Frisby stereo test. All visual measurements were carried out by a qualified optometrist under normal room illumination using the best-corrected spectacle prescription for that distance as determined by subjective refraction.

Visual field assessments were conducted using a Humphrey Field Analyzer (Carl Zeiss Meditec, Inc., Dublin, CA, USA) SITA-standard 30-2 threshold test. All participants were tested monocularly wearing their best near correction. Care was taken to ensure that the blind spot was located as accurately as possible in the visually impaired participants, which subsequently resulted in the correct retinal locations being used for the integrated binocular VF<sup>10,23-25</sup> as follows: Monocular field plots were combined using the "best location method," taking the most sensitive score at a given point to provide a binocular plot. The binocular plot was subdivided into areas of central 5°, central 10°, midperipheral (10°-30°), and a mean threshold determined for each area (Fig. 1). The assessment of the different extents of the binocular VF in this manner was based on published work that investigated the association between VF and the assessment of vision<sup>24</sup> and perceived difficulty with performing daily living tasks.<sup>25</sup> Visual function scores are presented in Table 1.

### Protocol

Kinematic data were collected using a six-camera three-dimensional motion analysis system (Vicon 460, Oxford Metrics Ltd., Oxford, UK). Six retro-reflective markers were attached to participants' dominant hand (distal border of the thumbnail and index fingernail, the proximal interphalangeal joint of the index finger, the metacarpo-phalangeal joint of the

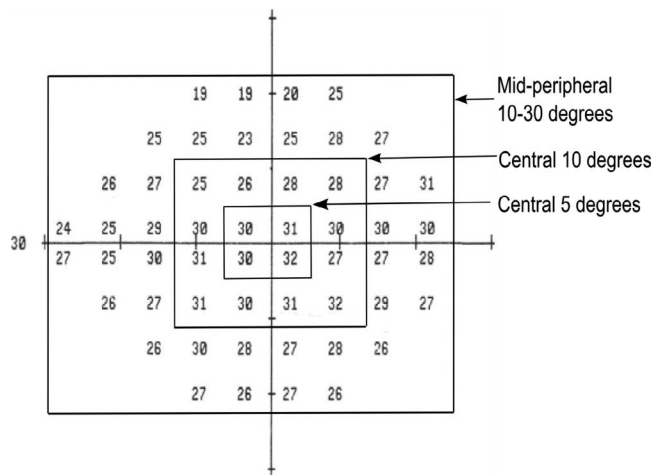


FIGURE 1. Integrated binocular visual field plot for a visually normal participant with the central 5° and 10° and midperipheral 10° to 30° grids overlaid.

index finger and thumb, and the radial styloid process on the wrist). A single marker was placed centrally on the top of each of the cylindrical objects.<sup>10</sup>

Participants were seated comfortably in front of a table (120 × 80 cm) that was covered with a black cloth. Using a precision grip (the thumb and the index finger), participants were required to reach toward and pick up either a small (30 × 100 mm diameter × height) or large (80 × 100 mm diameter × height) white cylindrical object from either a “near start” position (360 mm) or “far start” position (560 mm) position (reach-to-grasp phase). Once they had picked up the object, participants were required to “transport it” to either a “near end” position that was marked with a white cross “+” (20 × 20 mm), which was placed 150 mm to the side of the start location, or a “far end” position that was 350 mm to the side of the start location (transport-to-place phase; Fig. 2). All the position marks were visible on all trials. The object that was to be picked up was positioned centrally and directly in front of the participant. The transport phase was a movement away (or outward) from the body (movement from medial to lateral) and not across the body.

Pilot work determined that placing the object at end position “far” (350 mm) was within the region in which participants could comfortably transport the object without having to assume an unnatural/uncomfortable position. Care was taken to ensure that each participant was positioned at approximately the same height from the table (for consistency of eccentric angle) prior to starting the movement. This methodology is also explained in detail in Timmis and Pardhan.<sup>10</sup>

TABLE 1. Participant Demographics

Parameter	CFL (±SD)	PFL (±SD)	Control (±SD)	ANOVA
Age, y	77 (7)	74 (8)	76 (6)	
Distance VA, logMAR	0.83 (0.38)	−0.08 (0.16)	−0.04 (0.09)	G (CFL/PFL CFL/norm)
CS, Log	1.06 (0.27)	1.56 (0.10)	1.71 (0.10)	G (CFL/PFL CFL/norm PFL/norm)
Stereopsis, second of arc	Only 2/17 had measurable stereopsis	77.59 (99.32)	59.00 (16.30)	Only PFL and control analyzed
Visual fields				
Central 5°	15.00 (6)	24.23 (7)	32.33 (3)	G (CFL/PFL CFL/norm)
Central 10°	16.32 (5)	23.32 (6)	29 (3)	G (CFL/PFL CFL/norm PFL/norm)
Midperipheral 10°–30°	16.59 (5)	18.12 (6)	27.93 (2)	G (CFL/PFL CFL/norm PFL/norm)

Group means (±SD) are given for the different vision groups. Significant effects ( $P < 0.05$ ) are shown in the last column if there is a significant effect for the vision Group (G).

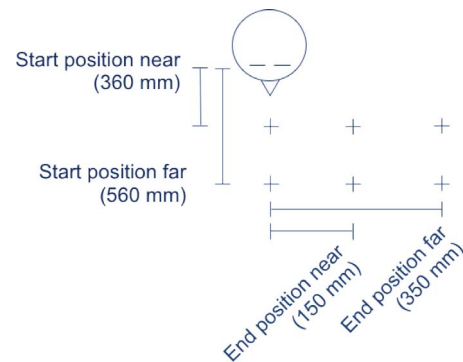


FIGURE 2. Participants reached out and picked up the object and then transported-to-place it at a predetermined location.

Participants started the task with their dominant hand placed on the edge of the table, 200 mm from their midline (approximately in line with the shoulder). In order to prevent participants from viewing the target and where it was placed prior to the start of the trial, they were instructed to look straight ahead and close their eyes.

Once participants had closed their eyes, one of the two objects (small or large) was then placed in front of the participant, in either the near or far location. Participants were instructed that, on hearing the word “go,” they should open their eyes, reach forward, and pick up the object and were also instructed to reposition it at either the near or far end position. Participants were made aware that they were to be timed whilst completing the movement but that they should complete the task as they would when performing similar everyday activities, and to reposition the object as accurately as possible. Participants did not receive any other information prior to the start of the movement, and all parameters (object size and object start and end position) were fully randomized. All trials were completed under binocular viewing condition, with participants optimally corrected for a reach of 46 cm, the average distance between the two object start positions.

All participants were given sufficient training to ensure that they were familiar with the protocol prior to the experiment. Prior to the start of the experiment, participants completed a pretest in which they grasped both the large and small objects at each initial start position and placed it in each end position. These practice trials were not counted in the main experiment, and participants were allowed to reposition/move the object after it had been placed on the table if they thought they could be more accurate. Participants were instructed to take as much time as they required to place the object as accurately as possible, with emphasis placed on accuracy rather than speed.

In the main test, no change of the object position was permitted; once the object had been repositioned on the table, it was not allowed to be moved. The “x” and “y” coordinates

TABLE 2. Kinematic Indices and Their Definitions

Variable	Definition
<b>Reach-to-grasp</b>	
Overall movement time	Time from when wrist marker velocity first exceeds 50 mm.s <sup>-1</sup> for 5 consecutive frames until object marker velocity first exceeds 10 mm.s <sup>-1</sup> for 5 consecutive frames (reach-to-grasp phase end).
Reaction time	Time between “go” command and when wrist marker velocity first exceeds 50 mm.s <sup>-1</sup> for 5 consecutive frames.
Maximum grip aperture	Maximum distance between thumb and forefinger from movement initiation until reach-to-grasp phase end.
Peak velocity	Peak forward velocity of the wrist marker.
Time to peak velocity	Time from “go” command to peak velocity.
Deceleration time	Time from peak velocity until end of reach-to-grasp phase.
Forward velocity corrections	Additional movements in the forward velocity profile after peak velocity until end of reach-to-grasp phase. Typically, in a movement that is either poorly planned or uncertain, once the peak velocity has been attained a number of online corrections are required. These online corrections are evidenced by additional forward peaks/corrections in the velocity profile.
Time after maximum grip aperture	Time after maximum grip aperture until end of reach-to-grasp phase.
<b>Transport-to-place</b>	
Transport duration	Time between the initiation of the transport-to-place phase (object marker velocity first exceeds 10 mm.s <sup>-1</sup> for 5 consecutive frames) to end of the transport-to-place (object marker velocity remains less than 100 mm.s <sup>-1</sup> for 5 consecutive frames).
Peak lateral velocity	Maximum wrist velocity in lateral direction from initiation to end of the transport-to-place phase.
Time to peak lateral velocity	Time between transport movement initiation and peak lateral velocity.
Number of velocity corrections	Additional movements in the lateral and vertical velocity profiles after peak transport velocity is reached to the end of transport-to-place phase end.
Deceleration time	Time from peak velocity until end of transport-to-place phase.
Object placement error	Resultant “x” and “y” coordinates of the object marker at the end of the trial, in comparison to the appropriate pretest trial.
Peak wrist height	Peak vertical height of the wrist during the transport-to-place phase.
Movement trajectory	The total distance travelled in the transport and place phase.

from each object placement were recorded through the Vicon motion capture system, and the accuracy (in terms of errors) of each subsequent object placement in the main experiment was examined. A total of 24 trials for each participant was completed; three repetitions of each object size (×2), start position for the reach-to-grasp phase (×2), and end position for the transport-to-place phase (×2).

Data were captured at 100 Hz (100 frames per second). Marker trajectory data were filtered using the cross-validated quintic spline smoothing routine with “smoothing” options set at a predicted mean squared error (MSE) value of 10 and processed using Vicon Nexus (Oxford Metrics Ltd). The MSE has units mm<sup>2</sup>. Applying the MSE method to the Woltring Filter allows one to control the “noise” level in the raw data. Fitting a spline to the data (raw data) of a set value allows a given level of tolerance for all data. This processing method is preferred by our research group compared to other approaches (such as generalized cross validation smoothing) as one can standardize the noise level across all trajectories.

Pilot work previously undertaken in our laboratory determined the most suitable MSE smooth filtering value to apply to the processed data. This consisted of analyzing different marker trajectories across a range of markers, processed using a range of smoothing options (no smoothing, auto function, and MSE value ranging from 5–20 mm<sup>2</sup>). When the automatic smoothing option was applied to the data, the trajectory was similar to the no smoothing option, and failed to filter out the noise inherent within the data. Using an MSE smooth filtering value ranging from 5 to 20 mm<sup>2</sup> filtered out this noise (determined through visual inspection). Removing the noise inherent within the data allowed stricter criteria to be used to determine key points within the movement, for example the onset of hand movement.

Previous studies have adopted a range of criteria to define movement parameters/onset ranging from 10 to 50 mm.s<sup>-1</sup>.<sup>3,10,26</sup> It is, therefore, common in human movement literature for the criteria of movement onset to vary slightly. We adopted two different approaches to confirm movement. Velocity thresholds were chosen based on pilot data that inspected the start and end of the movement, agreeing with previous studies.<sup>3,26</sup> The requirement for  $\geq 50$  mm.s<sup>-1</sup> to be maintained for five consecutive frames prevented “false starts” or “twitches” being defined as movement onset. We adopted the threshold that most accurately defined the key aspects of the movement (e.g., onset).

Details of the kinematic indices measured are given in Table 2. All have previously been documented to be important indicators of reach-to-grasp and transport-to-place performance.<sup>10</sup>

### Statistical Analysis

Normality of the data was confirmed using the Kolmogorov-Smirnov test ( $P > 0.05$ ). Separate mixed design  $2 \times 2 \times 2 \times 3$  (object size  $\times$  start location  $\times$  end location  $\times$  group) ANOVAs, with repeated measures for each factor, were used to analyze the processed data. Where appropriate, Tukey’s was used to conduct post hoc analyses. Pearson’s correlation coefficient was used to determine relationships between vision and kinematic measures (averaged across all conditions). The significance level for all statistical calculations was set at  $P < 0.05$ .

### RESULTS

From the 1056 trials completed within the study, the object was only knocked over on three occasions (all by CFL

TABLE 3. Reach-to-Grasp (R-G) Phase Movement Kinematics

Reach-to-Grasp (R-G) Phase	CFL ( $\pm$ SD)	PFL ( $\pm$ SD)	Controls ( $\pm$ SD)	ANOVA
Overall movement time, s	1.74 (0.24)	1.37 (0.26)	1.22 (0.36)	G, S, P, G/P
Reaction time, s	0.80 (0.12)	0.59 (0.12)	0.50 (0.16)	G
Maximum grip aperture, mm	92 (6.51)	100 (6.16)	98 (8.39)	S, P
Peak velocity, mm/s	701 (63)	705 (68)	734 (98)	P
Time to reach peak velocity, s	0.59 (0.08)	0.62 (0.08)	0.49 (0.10)	P
Deceleration time, s	1.25 (0.03)	0.74 (0.04)	0.73 (0.02)	G, S, P, G/P
Velocity corrections, <i>n</i>	16 (3)	6 (3)	3 (4)	G, P, G/P
Time from maximum grip aperture, s	0.89 (0.19)	0.465 (0.20)	0.36 (0.25)	G, P, G/S

Group means ( $\pm$ SD) are given for the different vision groups. Significant effects ( $P < 0.05$ ) are shown in the last column if there is a significant effect for the vision group (G), size of the object (S), position of the object (P), or any interaction effects (e.g. G/P indicates a significant interaction between Group and Position of the object; G/S indicates a significant interaction between Group and Size of the object).

participants when initially being grasped). These trials were discarded from the analysis. None of the objects fell over when being repositioned at the end position or were placed in the wrong end position.

### Reach-to-Grasp Phase

Table 3 shows the group means and statistical analysis of the reach-to-grasp movement between the groups.

### Overall Movement Time

There was a significant main effect of overall movement time by group ( $P = 0.02$ ). Post hoc analysis showed that CFL participants took longer to complete the movement compared to participants with PFL and controls (control  $P = 0.01$ ; PFL  $P = 0.03$ ). There was also a significant interaction effect between group and position of the object ( $P = 0.002$ ) as shown in Figure 3. Movement time when picking up the further object compared to the near object was significantly longer in the CFL group compared to the other two groups. Movement time was also influenced by the size of the object ( $P = 0.005$ ); however, there were no interaction effects between group and size of the object.

### Reaction Time

Movement initiation time was significantly affected by the group ( $P = 0.002$ ). Participants with CFL took longer to start the movement compared to participants with PFL and controls (control  $P = 0.001$ ; PFL  $P = 0.007$ ).

### Maximum Grip Aperture

There was no significant main effect of group for maximum grip aperture ( $P > 0.05$ ).

### Peak Velocity and Time to Reach Peak Velocity

Peak velocity and time to reach peak velocity were not significantly different between the three groups. Peak velocity and time taken to reach peak velocity were significantly greater when the object was located in the far start position ( $P < 0.001$ ). There were no other significant main effects or interactions ( $P > 0.05$ ).

### Deceleration

There was a significant main effect of deceleration by group ( $P = 0.0004$ ) as shown in Figure 4. Deceleration was significantly longer for CFL participants when compared to PFL participants and controls ( $P = 0.0016$ ). There was a significant interaction

between group and the position of the object ( $P = 0.005$ ) showing that CFL participants took significantly longer when the object was located in the far start position compared to PFL and controls.

### Velocity Corrections

There was a significant main effect of the group for the number of velocity corrections made ( $P = 0.004$ ). Post hoc analysis showed a significant difference between CFL participants and controls and PFL participants ( $P < 0.05$ ). A significant interaction between group and position showed that CFL participants needed to make more velocity corrections when picking up the object that was placed further away as seen in Figure 5.

### Time After Maximum Grip Aperture

The time taken after maximum grip aperture showed a significant main effect for the group ( $P = 0.013$ ). Post hoc analysis showed that CFL participants were significantly slower than PFL ( $P = 0.005$ ) and controls ( $P = 0.002$ ). There was also a significant group/size interaction. Central field loss participants took longer to complete the movement when the object was smaller, suggesting difficulties with the smaller object.

### Transport-to-Place Phase

Table 4 shows the group means and statistical analysis of the transport-to-place movement between the groups.

### Transport Duration

There was a significant main effect of overall transport duration ( $P = 0.002$ ). Central field loss participants took longer than PFL ( $P = 0.003$ ) and controls ( $P = 0.007$ ). There was also a significant group/position of the object interaction ( $P = 0.002$ ). Central field loss participants took longer to complete the movement when placing the object at the further location.

### Peak Lateral Velocity

There was no significant main effect of group on the peak lateral velocity. It was significantly faster when transporting the small object ( $P < 0.001$ ) and when placing the object in the far end position ( $P < 0.001$ ). There were no other significant effects or interactions.

### Time to Peak Lateral Velocity

There was no significant main effect of group on the peak lateral velocity.

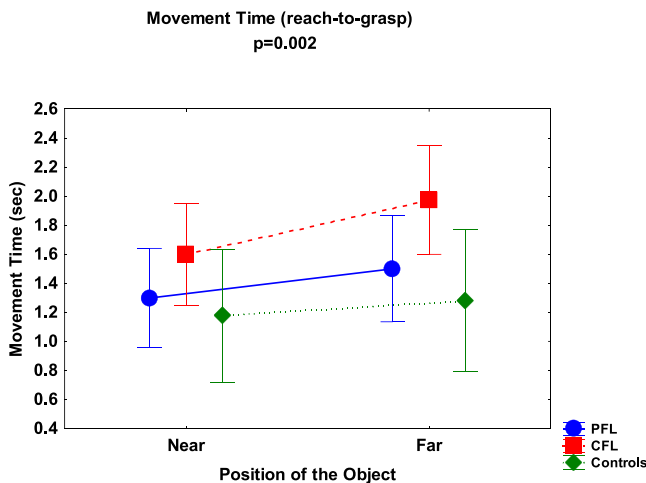


FIGURE 3. Movement time in seconds ( $\pm$ SD) during reach-to-grasp phase for the three groups when picking up the object in the near and far positions.

### Lateral Velocity Corrections

A significant main effect of group was shown ( $P = 0.002$ ). A greater number of velocity corrections were made by CFL participants when compared to PFL ( $P = 0.005$ ) and controls ( $P = 0.006$ ). Significantly more corrections were made when placing the object at the far end position, but there were no significant group/position interactions.

### Deceleration Time

Deceleration time was significantly affected by group ( $P = 0.048$ ). Post hoc analysis showed that CFL participants showed significantly slower deceleration times compared to controls ( $P = 0.04$ ) and PFL participants ( $P = 0.040$ ).

### Object Placement Errors

The resultant error in object placement showed a significant main effect for group ( $P = 0.001$ ). Central field loss had significantly greater error in object placement when compared to PFL ( $P = 0.0016$ ) and controls ( $P = 0.0019$ ). There was a significant

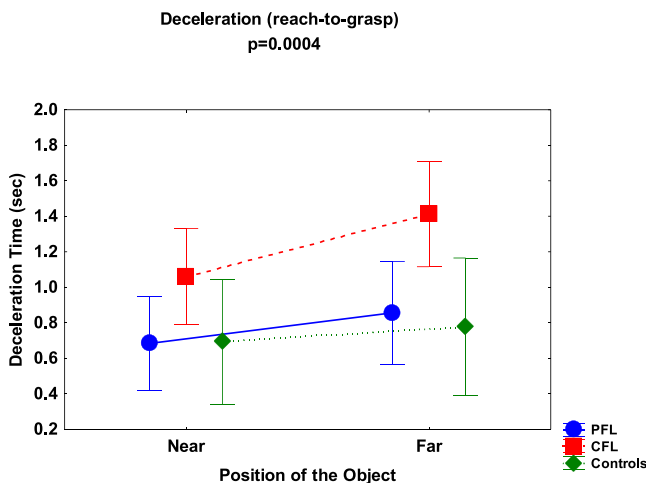


FIGURE 4. Deceleration time in seconds ( $\pm$ SD) during reach-to-grasp phase for the three groups when picking up the object in the near and far positions.

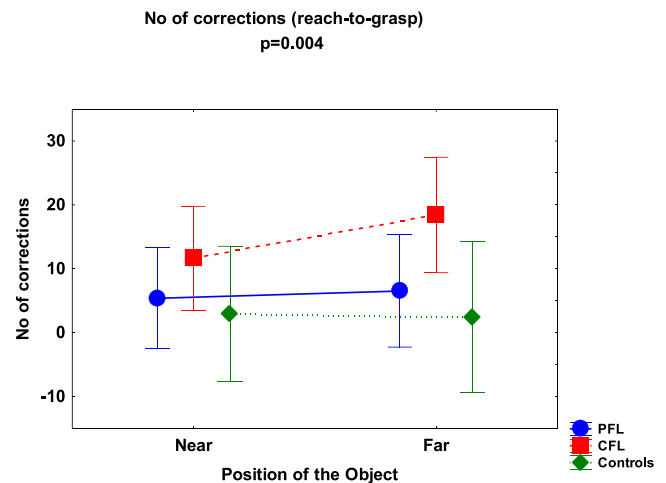


FIGURE 5. The number of velocity corrections ( $\pm$ SD) during reach-to-grasp phase for the three groups when picking up the object in the near and far positions.

interaction between group and size of the object ( $P = 0.02$ ). Central field loss participants made significantly more errors when placing the larger object compared to the smaller object.

### Peak Vertical Height of the Wrist

There was a significant main group effect ( $P = 0.0001$ ). The peak vertical height of the wrist was significantly higher in CFL group compared to PFL ( $P = 0.002$ ) and controls ( $P = 0.001$ ).

### Movement Trajectory

There was a main effect of the group ( $P = 0.0018$ ). The distance travelled by the CFL was significantly longer when compared to PFL ( $P = 0.010$ ) and control participants ( $P = 0.004$ ).

## CORRELATION ANALYSIS

### Reach-to-Grasp Phase

All data were pooled together (CFL, PFL, and controls) for correlation analyses (with Bonferroni correction applied). See Table 5. For stereopsis, only data for PFL participants and normals were used in the analysis. Visual acuity and CS were significantly correlated to overall movement time, reaction time, deceleration time, number of velocity corrections, and time spent after maximum grip aperture. The central visual field (averaged across  $5^\circ$ ) was also significantly correlated to overall movement time, reaction time, deceleration time, and number of velocity corrections. Figure 6 shows the overall movement time plotted against VA.

### Transport-to-Place Phase

Table 6 shows the Pearson's correlation analyses for all the data pooled together (CFL, PFL, and controls) and the transport-to-place indices (Bonferroni correction applied). For stereopsis, only data for PFL participants and normals were used in the analysis. Visual acuity showed significant correlation with transport duration, peak velocity, velocity corrections, and movement trajectory, while CS was significantly associated with transport duration and peak velocity. Interestingly, the visual field was not significantly correlated to the transport-to-place indices.

TABLE 4. Transport-to-Place (T-P) Phase Movement Kinematics

Transport-to-Place (T-P) Phase	CFL ( $\pm$ SD)	PFL ( $\pm$ SD)	Controls ( $\pm$ SD)	ANOVA
Transport duration, s	2.02 (0.19)	1.45 (0.19)	1.39 (0.25)	G, P
Peak lateral velocity, mm/s	449 (51)	509 (50)	507 (66)	P, S
Time to peak lateral velocity, s	0.59 (0.07)	0.58 (0.07)	0.48 (0.08)	P
Lateral velocity corrections, <i>n</i>	71 (10)	42 (11)	41 (13)	G, P/G
Deceleration time, s	1.58 (0.04)	0.95 (0.03)	1.00 (0.04)	G
Object placement error, mm	11.11 (1.94)	7.12 (1.88)	5.17 (1.58)	G, S, G/S
Peak wrist height, mm	133 (13)	86 (12)	87 (17)	G, P
Movement trajectory, mm	155 (15)	87.75 (14)	68.16 (19)	G, S, P

Group means ( $\pm$ SD) are given for the different vision groups. Significant effects ( $P < 0.05$ ) are shown in the last column for the vision group (G), size of the object (S), placement of the object (P), or any interaction effects (e.g., G/P indicating a significant interaction between Group and Placement of the object).

## DISCUSSION

Manual prehension tasks that involve reaching and grasping an object, and then transporting it accurately to another location are important activities of daily living. In order to further understanding of the impact of central and peripheral visual impairment on daily function, the reach-to-grasp and transport-to-place movements in participants with CFL and PFL were examined using three-dimensional motion analysis. The movement kinematics of the reach-to-grasp element and also of the transport-to-place phase, and the accuracy of final object placement were examined. The study extends the previous work carried out with CFL participants with AMD<sup>9-14</sup> on reach-to-grasp performance, including from our own laboratory,<sup>10</sup> which also examined transport-to-place the object at another location, by directly comparing the performance between CFL and PFL participants. It also extends previous research carried on glaucoma patients with typical PFL losses<sup>15</sup> by exploring the additional transport-to-place phase of the movement. The additional transport-to-place places a greater visual demand on the participant compared to previous reach-to-grasp tasks, and it reflects a more realistic task found in the home/kitchen. The relationships between the severity of VF loss as measured by VA and visual fields and the key kinematic indices were also explored. Our study showed various significant differences between participants with CFL and PFL.

## Reach-to-Grasp Phase

Our data showed that, when compared to PFL participants and normals, CFL participants took longer to start and complete the movement as shown by longer reaction times and overall movement times. As expected, all three groups took longer to reach out and grasp the object that was placed further away. However, participants with CFL took significantly longer to complete the movement for the object placed further away when compared to PFL and normals (indicated by a significant interaction effect, Table 3). This was most certainly due to their reduced ability to accurately ascertain where the object was and how far it was as it would have been obscured/blurred by their reduced central vision, which would have also affected their judgment of how far it was. Once the movement had started, the peak vertical velocity did not show any significant difference between the groups, indicating the first phase of the movement (the preplanning feed-forward phase) toward the object to be similar. This suggests that participants with CFL can carry out the initial phase of the movement as well as normal subjects and those with PFL. However, once they had attained the peak velocity, online movements were significantly different. Participants with CFL needed more online time for the latter part of the reach (shown by increased deceleration time and time after maximum grip aperture was reached), indicating uncertainty in their ability to complete the movement once it had started, and also deciding where the object was in relation to their wrist/hand. This uncertainty is also evidenced by the increased number of velocity corrections made, demonstrating that participants with CFL made more corrective (or “jerky”) movements when reaching out to the object. While normal and glaucoma participants with good central vision would have used the visual information gained from the fovea (the area of the eye that provides the highest amount of visual resolution to the eye) to carry out the task as accurately as possible, participants with CFL with degraded central visual information would have had to rely on impoverished visual information from the fovea or use a more eccentric point on the retina (commonly referred to as a preferred retinal locus), which has a poorer visual resolution and reduced fixation stability compared to the fovea, resulting in reduced performance. Our data on maximum grip aperture did not differ from that in a study by Timberlake et al.,<sup>9</sup> who also showed no difference in maximum grip scaling with binocular conditions as they reported larger maximum grip aperture only in monocular conditions.

## Transport-to-Place Phase

In comparison to both PFL and control participants, CFL participants took significantly longer to complete the move-

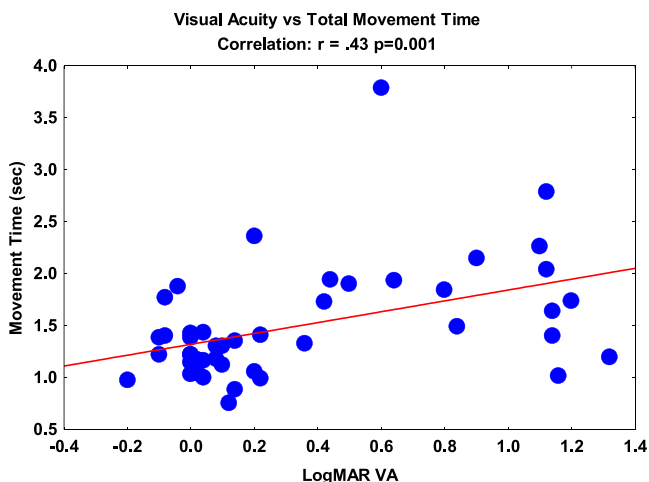


FIGURE 6. Pearson's correlation coefficient for logMAR VA and movement time (reach-to-grasp phase) for all participants.

TABLE 5. Pearson's Correlation Coefficients (*r*) Between Different Movement Kinematics (for the Reach-to-Grasp Phase) and Visual Function

Reach-to-Grasp (R-G) Phase	VA		CS		Stereopsis		Central 5°		Central 10°		Midperipheral 10°–30°	
	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>
Movement time	<b>0.43</b>	<b>s</b>	<b>-0.52</b>	<b>s</b>	-0.09	0.650	<b>-0.49</b>	<b>s</b>	<b>-0.45</b>	<b>s</b>	<b>-0.45</b>	<b>s</b>
Reaction time	<b>0.48</b>	<b>s</b>	<b>-0.44</b>	<b>s</b>	-0.19	0.325	<b>-0.41</b>	<b>s</b>	-0.30	ns	-0.29	ns
Maximum grip	-0.18	ns	0.16	ns	-0.04	0.830	0.28	ns	0.21	ns	0.19	ns
Peak velocity	-0.43	ns	0.48	ns	-0.16	0.540	0.37	ns	0.34	ns	0.42	ns
Deceleration time	<b>0.51</b>	<b>s</b>	<b>-0.55</b>	<b>s</b>	-0.10	0.602	<b>-0.51</b>	<b>s</b>	<b>-0.44</b>	<b>s</b>	<b>-0.41</b>	<b>s</b>
Velocity corrections	<b>0.49</b>	<b>s</b>	<b>-0.53</b>	<b>s</b>	-0.17	0.381	<b>-0.44</b>	<b>s</b>	<b>-0.40</b>	<b>s</b>	<b>-0.43</b>	<b>s</b>
Time after max grip	<b>0.47</b>	<b>s</b>	<b>-0.56</b>	<b>s</b>	-0.10	0.598	-0.44	ns	-0.38	ns	-0.36	ns

*P*, statistical significance values; bold font denotes statistical significance. Bonferroni correction was applied to the data. For stereopsis, only data for PFL participants and controls were used in the analysis.

ment (shown by increased duration times), especially when they had to place the object at the far end position (indicated by a significant interaction between group and distance). Central field loss participants also needed more time (once movement had started) to make online corrections (evidenced by increased deceleration time), suggesting that more time in the final phase was needed to make corrective adjustments, which indicated uncertainty about where the end position was in order to place the object. The increased deceleration time would allow for a longer opportunity to make online corrective adjustments in order to reduce the errors between the actual and required placement of the object (end position). The central field loss participants also demonstrated more corrective (or “jerky”) movements as indicated by lateral velocity corrections, demonstrating that they were uncertain with regards to the precise end position, and made more errors in placing the object accurately at its final predefined location. This indicates that they struggled in locating exactly where the final position of the object was.

Central field loss participants also lifted their wrist significantly higher, as suggested by increased wrist height, during the transport phase, when compared to PFL participants and normals. The longer movement trajectory and increased vertical wrist height shown by participants with CFL has also been noted in a previous study<sup>9</sup> in which participants with AMD showed a less “direct” reach when reaching-to-grasp an object. It is likely that increased central blur or the presence of central scotoma in these participants require them to exaggerate limb movements, which resulted in lifting their hands higher in order to circumvent the loss in their central vision. It could also indicate deficits in spatial awareness in these patients. The longer trajectory exhibited by CFL participants, shown by the longer path taken by the wrist, may well be a cautious strategy to try to reduce the risk of the wrist (and object) from contacting the table and causing either the object to be dropped or an injury. Participants with peripheral field defects did not need to do this as their central VFs were good.

Both CFL and PFL participants made more errors when placing the object at the final location, when compared to control participants. Participants with CFL were significantly worse than those with PFL, again highlighting the importance of the central field during transport-to-place tasks. This is most likely due to the errors in ascertaining the exact position of the peripheral location. All participants were less accurate when repositioning the large compared to the small object as a larger object with a greater diameter creates more uncertainty around the end-position location immediately prior to being placed compared to a smaller object that covers less area.

For precision tasks like these, a speed-accuracy trade-off usually exists (called Fitt's law), in which the longer time taken to complete a task results in better (more precise) performance. However, this was not shown by our CFL participants who, despite needing longer to complete the task, were still less accurate when placing the object accurately at the predefined location.

For the reach-to-grasp phase, data from CFL participants agree with Timberlake's study<sup>9</sup> who also showed increased reaction times, deceleration times, and movement durations. In addition, data from the present study show higher numbers of velocity corrections in participants with CFL especially for an object placed further away. Data for PFL participants also compare favorably to published research,<sup>15</sup> which reports a 100-ms difference in movement onset time between their glaucoma patients and normals. These data show a comparable mean difference of 90 ms (Table 2) between PFL and control participants. Kotecha et al.<sup>15</sup> also report a difference of 140 ms in their overall movement time, which compares to the slightly longer time of 150 ms between PFL participants and controls in the present study. However, some differences also exist between the two studies. Our data show little difference in online control (deceleration time) in PFL participants and controls while they show a significant difference in the comparable kinematic index of low-velocity phase.<sup>15</sup> A possible reason for this may be that, whilst most of the PFL

TABLE 6. Transport Phase Correlation Coefficients (*r*) Between Movement Kinematics (for the Transport-to-Place Phase) and Visual Function

Transport-to-Place (T-P) Phase	VA		CS		Stereopsis		Central 5°		Central 10°		Midperipheral 10°–30°	
	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>
Transport duration	<b>0.47</b>	<b>s</b>	<b>-0.41</b>	<b>s</b>	0.43	ns	-0.12	ns	-0.06	ns	-0.06	ns
Peak velocity	<b>-0.41</b>	<b>s</b>	<b>0.44</b>	<b>s</b>	0.26	ns	0.30	ns	0.26	ns	0.22	ns
Velocity corrections	<b>-0.42</b>	<b>s</b>	<b>-0.36</b>	ns	0.20	ns	0.10	ns	0.06	ns	0.323	ns
Deceleration time	0.34	ns	-0.32	ns	-0.02	ns	-0.91	ns	-0.21	ns	-0.18	ns
Error in placement	0.17	ns	-0.15	ns	-0.11	ns	-0.18	ns	-0.14	ns	-0.06	ns
Movement trajectory	<b>0.42</b>	<b>s</b>	<b>-0.38</b>	ns	0.09	ns	-0.14	ns	-0.10	ns	-0.05	ns

*P*, statistical significance values; bold font denotes statistical significance. Bonferroni correction was applied to the data. For stereopsis only, the data for PFL participants and normals were used in the analysis.



participants in the current study had primarily peripheral field defects, some of the glaucoma participants in a study by Kotecha et al.<sup>15</sup> had dense central field defects (for example, participant C had a small, dense inferior nasal central defect in one eye). This may well have interfered with online control, and this patient (and indeed others like him/her) may well have behaved like the CFL participants in our study who also show a significant decrease in deceleration time. Any further comparison is difficult due to the different object sizes, distances, and method of analysis between the two studies.

A comparison of our data to the study that simulated visual field defects<sup>7</sup> suggests that our CFL participants also show deficiencies in grasp and transport components, agreeing with the data of CFL in the simulated study. However, our PFL participants do not show the same deficiencies shown by the simulated peripheral defects. Various reasons may account for this including the different extent of peripheral fields in both studies (the visual field defects in our study were less drastic than the simulated study that used pinholes), as well as the impact of any visuomotor adaptation to visual loss and also head movements.<sup>11</sup>

Correlation analysis for the reach-to-grasp phase (Table 5), when all the VF data from all the participants were pooled together (with Bonferroni correction applied), showed that VA and CS were significantly correlated with five out of the seven kinematic indices (overall movement time, reaction time, deceleration time, number of velocity corrections, time spent after maximum grip aperture). In addition, central visual field (averaged across 5°) was also significantly correlated to four kinematic indices (overall movement time, reaction time, deceleration time, number of velocity corrections). This demonstrates that participants with reduced central VF (reduced VA, CS, and central 5°) took longer to start the movement, possibly because they needed more time to establish where the object was. Reduced central VF (reduced VA, CS, and central 5°) was also significantly correlated to increased deceleration times, possibly because participants struggled to accurately calibrate the distance between their wrist and the object, and to more corrective movements of their wrists (indicated by increased velocity corrections) most likely due to the uncertainty of determining exactly where the object was in relation to their wrist.

Correlation analysis for the transport-to-grasp phase (Table 6) showed that VA and CS were also the important parameters associated with this movement. Visual acuity was significantly associated with four kinematic indices (transport duration, peak velocity, velocity corrections, and movement trajectory), while CS was significantly associated with transport duration and peak velocity. Lower VA and CS increased the time to transport and place the object in the predetermined position. Reduced VA resulted in more corrective movements (increased lateral velocity corrections), increased wrist height (increased movement trajectory), needing more time to make online corrections (increased deceleration time) and also reduce overall speed (decreased peak velocity). Average peripheral field data had less influence on the transport-to-grasp parameters, suggesting that it is the status and integrity of central VF (mostly denoted by VA and CS) that are important when transporting an object to a more peripheral position.

The significant correlations with central VF (VA, CS) when all the data from three groups (normals, AMD, glaucoma) are pooled together for both reach-to-grasp and transport-to-grasp also suggest that it is not the etiology of the ocular disorder that determines how the participant will carry out the task but the integrity of the central VF; mostly shown by VA and CS (and averaged central 5° to an extent) that is important. Based on these correlation data, we postulate that participants with loss in central vision (irrespective of whether it is due to AMD or

glaucoma or indeed any other pathology that affects central vision) will have difficulties when carrying out a task that requires them to reach and grasp an object, but also to place to another location. We hypothesize that if central vision loss were to occur, for example even in participants with progressive glaucoma (or any other ocular disease), and VA and CS was reduced, a similar performance to that shown by participants with CFL will occur. Indeed, some of the individual cases with glaucoma who have CFLs in a previous study<sup>15</sup> support this. Exactly how the performance is affected by the progression of visual field defects into central domain needs to be investigated in a large number of patients (irrespective of how it was acquired—AMD, glaucoma, other ocular disease). Although the correlation data of this study give a good indication of how performance is affected over a range of central VF measures, further investigation is clearly warranted.

It has previously been shown that stereopsis is important for the reach-to-grasp phase of the movement.<sup>27,28</sup> In addition, Verghese et al.<sup>29</sup> demonstrated the influence of binocular vision and stereopsis in participants with CFLs on a task that required placing pegs on a board. Their data showed that two out of four indices (peg placement times and errors) were significantly different in participants who had stereopsis when compared to those who had no stereopsis, showing a positive influence of stereopsis on task performance. They also reported that stereoacuity was the only independent variable that was significantly correlated with the binocular-to-monocular performance of peg-placement time in participants with measurable stereoacuity, and that AMD patients with coarse stereoacuity showed similar peg-placement times compared to age-matched controls. As only two of our CFL participants had very gross stereopsis, it is difficult to directly compare our findings with that of the study by Verghese et al.<sup>29</sup> with regards to the contribution of stereopsis on CFL participants. It is possible that, had our CFL participants showed the same levels (and range) of stereopsis as their participants, then a significant correlation may have occurred between some of the kinematic indices in our study and stereo-acuity. Future research could investigate whether stereoacuity has a significant effect on this task by examining a larger number of PFL patients with a wider range of stereo-acuity. It is also possible that the Frisby test in our study did not pick up the existence of stereopsis as it uses small image sizes, which might have been difficult for our CFL participants. However, none of the participants reported difficulty in seeing the pattern on the target, and we are fairly confident that this was not a limitation.

The lack of any significant correlation of task performance with stereoacuity in PFL and normal participants was a surprising finding, but this also agrees with previous literature with glaucoma participants.<sup>15</sup> The small spread in data values in these two groups coupled with a lack of significant difference between the stereoacuity in PFL and normals (*t*-test  $P > 0.05$ ) may have contributed to this result. As suggested above, a study on a larger number of participants who have a larger spread of stereoacuity is therefore warranted.

The role of head movement in manual prehension has been examined previously. An earlier study<sup>30</sup> claimed that participants made fewer online corrections with monocular viewing when they were allowed to move their heads during manual prehension. However, this effect was not observed during binocular viewing. Our previous study has also shown that CFL participants exhibit significantly greater peak vertical head movements when compared to controls during obstacle crossing.<sup>10</sup> This may have occurred as the participants had little depth perception. It may be that our PFL participants moved their heads more in order to “clear” their PFL. On the other hand, as they had relatively good binocular vision and were considered to be within the normal stereo-acuity range,

the need for this might have been reduced. Due to the logistics of setting up the experiment to differentiate between head movement and eye movements for this particular task, this was not investigated in the present study but is an important consideration for future studies.

## CONCLUSIONS

Simply reaching out to grasp an object in itself is not generally representative of an everyday activity; the task would normally also include the act of transporting it to another location and placing it there. Findings of this study show that, when completing the full task, participants with CFL demonstrated worse performance compared to PFL participants. Correlation analysis suggests that it is the central VF (VA, CS, central visual fields) that is important in carrying out this task.

The results of this study suggest that CFL will influence activities of daily living that require participants to reach out to an object and then place it at another location, such as putting away groceries and various other tasks such as tidying up, organizing work tops, etc. It is therefore important that, from a rehabilitation and support point of view, due attention is given not only to participants with macular degeneration who are known to have CFLs, but to recognize that this should also be extended to other patients (e.g., glaucoma) in whom CFL has also occurred. A key finding from this research is that healthcare professionals/carers should be aware that, for patients with central field defects however acquired (AMD, glaucoma), such tasks may be difficult and this should be reflected in the healthcare they receive.

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