What is the Nature of the Reach-and-Grasp Deficit in Glaucoma?

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Funding : Société Française du Glaucome, 2015 (SFG)

Précis

In a reach-and-grasp task, patients with glaucoma exhibited a motor disorder, even when they had time to explore their environment. The motor performance of glaucoma patients should be taken into account in rehabilitation.

Abstract

Purpose: Vision plays an important role in planning and executing manual prehension (reaching and grasping). We assess the impact of glaucoma on motor production, as a function of the visual exploration time available to the patients.

Methods: We compared performance in two reach and grasp tasks determined by whether or not the participants (16 glaucoma patients, 14 age-matched and 18 young controls) had time to explore the objects before reaching and grasping a target object defined by its color.

Results: Differences were observed between glaucoma patients and age-matched controls on movement duration and peak velocity (reaching phase) only when participants were not provided time to look at the objects before the movement (immediate condition).

Conclusions: Glaucoma patients exhibited a motor disorder (grasping phase) only when they had no time to explore their environment before performing the reach-and-grasp task. The motor abnormalities in reaching phase observed in glaucoma patient in previous studies seem to result from difficulties in target identification rather than from visuo-motor deficits. From a clinical point of view, motor performances of glaucoma patients could be modulated by task, especially by temporal constraints of task.

Key Words

Glaucoma ; reach and grasp ; identification ; kinematics ; temporal constraints

Introduction

Glaucoma is an ocular disease that produces irreversible retinal ganglion cell and optic nerve fiber loss.[1] Visual deficit in glaucoma starts in the peripheral visual field and progresses towards the center. Most studies of glaucomatous vision loss assess relatively simple aspects of visual processing that are encoded in the retina (e.g. sensitivity to luminance increments as in typical perimetry or flickering gratings as in frequency-doubling technology perimetry), because glaucoma is considered primarily as a retinal ganglion cell disease.[2,3] Several studies have reported that advanced glaucoma also leads to difficulties with daily life activities such as driving, fear of falling and reading, and the feeling of a reduced quality of life.[4–6] Indeed, both peripheral[7,8], and central vision are needed for activities such as reading,[9,10] driving, facial recognition,[11] reaching for and grasping objects[12,13] or accomplishing natural actions.[5] In the case of motor action, the visual system provides critical information about the location, size, and shape of to-be-grasped objects which is used for planning the action. The activation of the motor command leads to hand acceleration towards the object (the "reach" phase). When approaching the object, the hand decelerates and the grip aperture is adapted to the object's size (the "grasp" phase). At this phase, vision provides corrective information to improve the grasp.[14–18] A visual deficit can disrupt the performance of a voluntary motor action, as shown in previous studies.[12,13,19] For instance, some studies have shown impairments in initial movement planning and control in patients with glaucoma[20] and in age-related macular degeneration,[12,13] or in grasping components in patients with amblyopia.[21] Kotecha et al. (2009) reported atypical kinematic characteristics in patients with glaucoma compared to normally sighted people: slower reaction time, longer overall movement duration, low-velocity phase (suggesting a deficit in the grasping phase). The same results

were found when healthy participants performed reach-and-grasp tasks with an artificially reduced visual field: longer overall movement duration, slower maximum velocity and higher maximum grip aperture.[7]

However, research on motor control suggests the existence of inverse models.[22,23] These inverse models suggest that planning of motor commands requires processing of all relevant sensory information. Once the motor command is executed, the motor action can achieve its objective without visual feedback even if, for control subjects, movements are more accurate and precise when visual feedback is available.[24] In line with these models, we hypothesize that increased time to explore a scene may result in decreased difficulty with a motor action for glaucoma patients. In other words, deficits in the motor performance of patients with visual impairment that have been reported in previous studies[20] might be due to the fact that they were not given enough time to analyze the environment prior to motor production rather than the result of motor system deficits itself. Indeed, in these studies, participants were presented with the target object at the very moment they had to grasp it, while in daily life, patients have time to look at an object before grasping it. Therefore, laboratory studies mix two components: (1) the effect of central visual impairment on motor production and (2) the effect of visual impairment on the time for perception of the spatial properties of the object (e.g., spatial location, distance and width), leading to a deficit in motor production. This distinction is important. For instance, motor production deficits in patients with age-related macular degeneration (AMD) seem due to visual impairment, not to motor production itself.[25] Therefore, patients with AMD just need more time to accomplish their daily life actions[26] instead of actual rehabilitation of their motor system production. In the present study, we assess the impact of glaucoma on the two components. The kinematics of the reach-and-grasp motor action was compared in two different conditions: one in which participants saw the object only at the moment they had to grasp it, thus measuring the effect

of a deficit in the analysis of the object's metrics on motor production, (i.e., with temporal constraints for visual exploration); and one in which they had time to observe the object before grasping it, thus measuring the effect of visual impairment on motor production (i.e., with no temporal constraints for visual exploration). We hypothesized that deficits in the kinematic parameters of glaucoma patients should be observed in the task with temporal constraints for visual exploration (immediate condition) rather than in the task with no temporal constraints for visual exploration (delayed condition). Indeed, in the first task, the participant needs to explore the environment quickly in order to initiate the action as soon as possible. Therefore, owing to glaucoma, the visual information is not entirely processed and the visual feedback, in order to adjust his (or her) action, is greater compared to the delayed condition. In the delayed condition, the observation time before grasping the object allows the planning of a motor command and the execution of the motor action at the appropriate moment. Therefore, visual feedback is less important for accomplishing a motor action compared to the immediate condition. We also investigated the relationship between each kinematic parameter and visual acuity to better understand the links between visual acuity of pathology in motor performance. Indeed, kinematic parameters are known to be influenced by visual acuity.[12,20,27]

Methods

Participants

Sixteen patients with primary open angle glaucoma (POAG) were recruited in the ophthalmology department of Claude Huriez Hospital, Lille, France. All participants underwent SITA-standard 30-2 perimetry with a Humphrey Visual Field Analyzer II (HFA, Carl Zeiss Meditec, Dublin, CA, USA), had glaucoma-related visual field (VF) defects and a mean deviation (MD) worse or equal to -6 dB (SITA-standard 30-2: MD = -16.4 ± SD = 5.76;

range: 8.6 - 27). They had to have a monocular visual acuity of 6/12 or more in the tested eye (best eye included in the recruitment criteria). If both eyes had equal acuity, one eye was randomly selected.

There were 14 volunteers with normal visual acuity among the age-matched participants. They were either relatives of participants with glaucoma or patients who had undergone successful cataract surgery, with normal visual acuity ranging from 20/25 to 20/20. Age-matched participants were recruited in the ophthalmology department of Claude Huriez Hospital, Lille, France. Controls were tested monocularly on their preferred eye. A young adult group included 18 healthy students (in medicine, neuroscience and psychology) with normal vision (visual acuity = 20/20). Young people were included as controls to dissociate the effect of ageing from the effect of pathology. All participants had one eye patched (the eye with lower acuity for patients). Demographic data are provided in Table 1. Clinical data are provided in Table 2.

/ Insert table 1 here /

/ Insert table 2 here /

A mini-mental state examination (MMSE)[28] was administered to the older participants. Participants with a history of neurological disease, psychiatric disease, cognitive impairment (MMSE < 25/30) or other ocular diseases (cataract, AMD) that might compromise oculomotor function were excluded. A physical therapist tested the participants for normal motion of the right arm and hand. All participants were right-handed. The study was approved by the ethics committee of Lille University. In accordance with the tenets of the Declaration of Helsinki, written informed consent was obtained from all participants.

Apparatus and material

Participants sat in front of a table (120x80 cm) and placed their thumb and index close to a starting point located 10 cm from the edge of the table (see Figure 1). Five cylinders (height: 10.5 cm, diameter: 5.5 cm) located on the table in a semi-circle (radius: 25 cm from the starting point) at 0° (center), 30° and 60° to the left and the right of the center cylinder were used as stimuli. The participants' head was positioned 60 cm from the central cylinder. All cylinders positioned on the table were the same color (wood color). Before each trial, they were (re)positioned in these five precise locations by the experimenter. In front of the table, a curved screen (180° degrees of eccentricity) displayed the different steps of each trial (fixation cross, five colored cylinders at five spatial locations, Figure 1). Participants performed two tasks in a random order: one with a temporal constraint for visual exploration (immediate condition) and one with no temporal constraint for visual exploration (delayed condition). Each condition involved 25 trials determined by five colors (blue; red; yellow; white; black) * five spatial locations (60° right; 30° right; 0°; 30° left; 60° left). A schematic representation of both tasks is shown in Figure 2. Before the experiment, each color cylinder was displayed and the participants had to recognize each color. All participants were able to name the colors of the five cylinders.

/Insert figure 1 here /

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In the task with a temporal constraint for visual exploration (immediate condition), participants placed their thumb and index on the starting point and looked at the fixation cross displayed on the curved screen. Simultaneously, the name of a color was given by a

loudspeaker 2000 ms +/- 500 ms and five colored cylinders were displayed on the curved screen in five different spatial locations (0° center, 30° left and right and 60° left and right). The colored cylinders and the spatial locations on the screen were changed randomly between participants and trials. Participants explored the displayed colored cylinders. As soon as they recognized the spatial location of the given color, the participants were instructed to reach and grasp as quickly and accurately as possible the cylinder on the table with the corresponding color. They were asked to lift it approximately 10 cm, put it on the table and return to the starting point.

In the task with no temporal constraint for visual exploration (delayed condition), the same procedure was used, except that participants were not to reach and grasp the cylinder as soon as they recognized the target color but only after an auditory cue. Participants placed their thumb and index on the starting point and then fixated the cross displayed on the curved screen. Simultaneously, a color was given by a loudspeaker 2000 ms +/- 500 ms and colored cylinders were displayed on the curved screen in five spatial locations (0°, 30° left and right and 60° left and right). The colored cylinders and spatial locations on the screen were changed randomly between participants and trials. Participants explored the displayed colored cylinders. Unlike in the immediate condition, participants had to wait for an auditory cue to reach and grasp the cylinder corresponding to the given color as quickly and accurately as possible. This cue occurred 2000 ms +/- 500 ms after the color was given. The time between the color name and the auditory cue allowed the exploration of the displayed cylinders. In this condition, the participants had time to identify the target cylinder and to prepare their reach-and-grasp movement. As soon as they heard the auditory cue, they had to reach and grasp the cylinder as quickly and accurately as possible, lift it approximately 10 cm, put it on the table and return to the starting point.

Data Recording and Analysis

A magnetic tracking system (Polhemus Liberty 240/8-8 System, Colchester, VT) was used to record the participants' movements in a X, Y and Z coordinates system. The kinematics of the reach-and-grasp movements and cylinder displacements were measured by eight markers that were placed on the index (base and tip), the thumb (tip), and the wrist (scaphoid and pisiform) of the participants. One additional marker was placed on each of the five cylinders. The spatial environment (table and cylinder) was calibrated before each session, allowing the system to reach a temporal and spatial resolution accuracy lower than 0.2 mm at a 240 Hz sampling rate.

All parameters were computed with a custom program (MatLab®; MathWorks®, Natick) based on the 3D coordinates of the reflective marker placed on the wrist, index and thumb of the participants and on the five markers on the cylinders. The kinematic outcome measures were computed on the basis of the wrist marker. Temporal and kinematic parameters of the (x, y, z) coordinates of the wrist marker were computed from tangential velocity profiles, after filtering the data using a second-order Butterworth dual-pass filter (cut-off frequency: 15 Hz). Movement onset was defined as the first velocity value reaching 0.3 cm/s.

The following kinematic parameters of the reach-and-grasp trajectories were calculated (Figure 3):

1. "Movement duration" corresponding to the time between movement onset and movement end (defined as the moment when participants reached the cylinder).

2. "Peak velocity" corresponding to the maximum velocity reached by the wrist during movement.

3. "Acceleration interval" corresponding to the time between the onset of hand movement and the “peak velocity” moment.

4. "Deceleration interval" corresponding to the time between “peak velocity” moment and the end of the movement.

5. "Maximum grip aperture" (MGA) corresponding to the maximum distance between thumb and index during movement.

6. "Time to maximum grip aperture" corresponding to the time between the onset of hand movement and the time of maximum grip aperture.

/Insert figure 3 here /

Trials were excluded from the data analysis when a participant responded erroneously. 1.6% of the trials, homogenously distributed across the conditions, were discarded. For each task, a 2x3 analysis of variance was conducted with each group {Glaucoma patients; Age-matched Controls; Young Controls} as the between-participants factor and angle condition {0°; 30° right; 30° left; 60° right; 60° left} as the within-participants factor. Local comparisons were performed using a post-hoc Bonferroni test with threshold corrections, in order to account for multiple group factor comparisons and possible interactions between Group and Angle. For the sake of clarity, principal effect of angle and post-hoc are not presented because we had no hypothesis on this factor. Spearman correlations for glaucoma patients were computed between each kinematic parameter, visual acuity, MD 30-2 and duration of pathology. Finally, comparisons of the results of the immediate condition vs delayed condition for each glaucoma patient were conducted. Results are presented in Tables 3, 4 and 5.

Results

Task with temporal constraints for visual exploration (immediate condition)

1. Movement duration

A group effect was observed on movement durations ($F_{(2, 45)} = 36.5$; $p < 0.001$; $\eta^2 = 0.6$). The movement duration of glaucoma patients ($X_{mean} = 1179$ ms; SD = 250 ms) was significantly longer than that of age-matched participants ($X_{mean} = 1001.8$ ms; SD = 169.6 ms; $p < 0.014$) and young participants ($X_{mean} = 680.2$ ms; SD = 106.5 ms; $p < 0.001$). The movement duration of age-matched participants was significantly longer than that of young participants ($p < 0.001$).

2. Peak velocity

A group effect was observed on peak velocity ($F_{(2, 45)} = 11.6$; $p < 0.001$; $\eta^2 = 0.27$). Peak velocity of glaucoma patients ($X_{mean} = 32.4$ cm/s; SD = 10.2 cm/s) was significantly faster than peak velocity of age-matched participants ($X_{mean} = 24.4$ cm/s; SD = 7.4 cm/s; $p = 0.002$) and young participants ($X_{mean} = 22.8$ cm/s; SD = 2.4 cm/s; $p < 0.001$). No significant difference was found between age-matched and young participants.

An interaction was found between group and angle on peak velocity ($F_{(8, 180)} = 2.17$; $p = 0.032$; $\eta^2 = 0.016$; Figure 4). The Bonferroni post-hoc comparison revealed that peak velocity for glaucoma patients was faster than peak velocity for age-matched participants and young participants, only at 60° eccentricity on the left (respectively $p = 0.05$ and $p = 0.002$) and right angles (respectively $p = 0.007$ and $p < 0.001$).

/ Insert figure 4 here /

3. Acceleration interval

A group effect was observed on the acceleration interval ($F_{(2, 45)} = 12.7$; $p < 0.001$; $\eta^2 = 0.27$). The acceleration interval of glaucoma patients ($X_{mean} = 358.4$ ms; SD = 107 ms; $p < 0.001$) and age-matched participants ($X_{mean} = 378.2$ ms; SD = 82.7 ms; $p < 0.001$) was significantly longer than that of young participants ($X_{mean} = 269.4$ ms; SD = 55 ms).

No interaction was found between group and angle on acceleration intervals.

4. Deceleration interval

A group effect was observed on the deceleration interval ($F_{(2, 45)} = 28$; $p < 0.001$; $\eta^2 = 0.52$). No difference was observed between glaucoma patients and age-matched participants. The deceleration interval of both glaucoma patients ($X_{mean} = 860.4$ ms; SD = 230 ms; $p < 0.001$) and age-matched participants ($X_{mean} = 760.4$ ms; SD = 139 ms; $p < 0.001$) was significantly longer than that of young participants ($X_{mean} = 458.6$ ms; SD = 129.8 ms).

An interaction was found between group and angle on the deceleration interval ($F_{(8, 180)} = 4.53$; $p < 0.001$; $\eta^2 = 0.014$). The Bonferroni post-hoc comparison revealed differences for glaucoma patients and age-matched participants in comparison to young participants ($p < 0.001$) for all angles (except young versus age-matched participants for 60° right ($p = 0.02$) and 60° left ($p = 0.003$)).

5. Maximum grip aperture

No group effect was observed on maximum grip aperture. Maximum grip aperture of glaucoma patients (X_{mean} = 8.96 cm; SD = 1.82 cm) was not significantly different from the maximum grip aperture of age-matched participants (X_{mean} = 8.88 cm; SD = 1.04 cm) and young participants (X_{mean} = 9.47 cm; SD = 1.09 cm).

An interaction was found between group and angle on maximum grip aperture ($F_{(8, 180)}$ = 1.21; p = 0.03; η^2 = 0.017). The Bonferroni post-hoc comparison revealed a difference between 60° right (X_{mean} = 8.62 cm; SD = 2.38 cm) and 60° left (X_{mean} = 9.31 cm; SD = 1.87 cm) for glaucoma patients only (p = 0.034).

6. Time to maximum grip aperture

A group effect was observed on time to maximum grip aperture ($F_{(2, 45)}$ = 23.7; p < 0.001; η^2 = 0.42). The time to maximum grip aperture of glaucoma patients (X_{mean} = 716.4 ms; SD = 191 ms; p < 0.001) and age-matched participants (X_{mean} = 665.4; SD = 98 cm; p>0.001) was significantly shorter than that of young participants (X_{mean} = 463.6 cm; SD = 102.1 cm).

No interaction was found between group and angle on time to maximum grip aperture.

/ Insert Table 3 here /

Finally, correlations were found between visual acuity for glaucoma patients and movement duration, deceleration interval and time to MGA (for 60° left condition only),

suggesting a link between deficit intensity and deficit of movement kinematic parameters (Table 3 and Figure 5).

/ Insert Figure 5 here /

To summarize (Table 4), in the immediate condition, participants with glaucoma had significantly longer movement duration and higher peak velocity than age-matched and young participants. This result indicates an effect of glaucoma on the reaching phase of the movement. Interestingly, peak velocity for glaucoma patients was higher for cylinders located in the peripheral field of vision (60° left and right angle), thus suggesting that the deficit in movement kinematics is related to the visual field deficit.

/Insert Table 4 here /

/Insert Table 5 here /

Task with no temporal constraints for visual exploration (delayed condition)

1. Movement duration

A group effect was observed on movement durations ($F_{(2, 45)} = 41.4$; $p < 0.001$; $\eta^2 = 0.63$). The movement duration of glaucoma patients ($X_{mean} = 1251.4$ ms; SD = 242.2 ms) was significantly longer than that of age-matched participants ($X_{mean} = 1066$ ms; SD = 175 ms; $p = 0.02$) and young participants ($X_{mean} = 716$ ms; SD = 110.8 ms; $p < 0.001$). The movement duration of age-matched participants was significantly longer than that of young participants, $p < 0.001$)

An interaction was found between Group and Angle on movement duration ($F_{(8, 180)}$ = 2.99; p = 0.004; η^2 = 0.006). No significant differences were observed between the movement duration of glaucoma patients and age-matched participants for all angles. The movement duration of glaucoma patients and age-matched participants was significantly longer than that of young participants (p < 0.01 for all angles, except age-matched versus young participants at 60° left (p = 0.007)).

2. Peak velocity

A group effect was observed on peak velocity ($F_{(2, 45)}$ = 5.06; *p* = 0.01; η^2 = 0.108). Peak velocity of both glaucoma patients (X_{mean} = 39.2 cm/s; SD = 11.7 cm/s) and age-matched participants (X_{mean} = 40.1 cm/s; SD = 10.7 cm/s) was significantly faster than that of young participants (X_{mean} = 32.9 cm/s; SD = 5.3 cm/s; respectively p = 0.05 and p = 0.02).

No interaction was found between group and angle on peak velocity.

3. Acceleration interval

A group effect was observed on the acceleration interval ($F_{(2, 45)}$ = 6.03; *p* = 0.005; η^2 = 0.157). The acceleration interval of glaucoma patients (X_{mean} = 390.8 ms; SD = 100.6 ms; p = 0.06 (trend)) and age-matched participants (X_{mean} = 413 ms; SD = 109.6 ms; p = 0.006) was significantly longer than that of young participants (X_{mean} = 327 ms; SD = 42.1 ms).

An interaction was found between group and angle on acceleration intervals ($F_{(8, 180)}$ = 3.34; p = 0.001; η^2 = 0.036). The Bonferroni post-hoc comparison revealed a difference between age-matched and young participants at 30° left angle (p = 0.004).

4. Deceleration interval

A group effect was observed on the deceleration interval ($F_{(2, 45)}$ = 59.2; p < 0.001; η^2 = 0.704). The deceleration interval of glaucoma patients (X_{mean} = 860.4 ms; SD = 162.8 ms; p < 0.001) was longer than that of age-matched participants (X_{mean} = 651.6 ms; SD = 138 ms; p < 0.001) and young participants (X_{mean} = 389.4 ms; SD = 95.7 ms). The deceleration interval of age-matched participants was longer than that of young participants (p < 0.001).

No interaction was observed between group and angle.

5. Maximum grip aperture

A group effect was observed on maximum grip aperture ($F_{(2, 45)}$ = 3.5; p < 0.04; η^2 = 0.13). The maximum grip aperture of glaucoma patients (X_{mean} = 8.7 cm; SD = 1.4 cm) was not significantly different from that of age-matched participants (X_{mean} = 8.8 cm; SD = 1cm). A tendency was observed between the maximum grip aperture of glaucoma patients and that of young participants (p = 0.079). (X_{mean} = 9.6 cm; SD = 1 cm, p = 0.08).

No interaction was found between group and angle on maximum grip aperture.

6. Time to maximum grip aperture

A group effect was observed on time to maximum grip aperture ($F_{(2, 45)} = 19.2$; $p < 0.001$; $\eta^2 = 0.29$). A Bonferroni post-hoc comparison revealed a significant interaction between the time to maximum grip aperture of both glaucoma patients ($X_{mean} = 804.2$ ms; SD = 253.2 ms) and age-matched participants ($X_{mean} = 727$; SD = 148 cm) with young participants ($X_{mean} = 496.8$ cm; SD = 86.1 cm, $p < 0.001$).

No interaction was found between group and angle on time to maximum grip aperture.

Finally, no correlation was found between visual acuity and kinematics parameters for glaucoma patients.

To summarize (Table 5), in the delayed condition, glaucoma patients had significantly longer movement duration and deceleration interval than age-matched and young participants. This result indicates an effect of glaucoma on the grasping phase of the movement. Interestingly, the deceleration deficit in glaucoma patients was not affected by the location of the cylinder, suggesting that it does not depend on the location of the visual field deficit.

Comparison between the immediate versus delayed conditions for each glaucoma patient

No statistical difference was observed between immediate and delayed tasks for each glaucoma patient on movement durations, deceleration interval, maximum grip aperture and time to maximum grip aperture.

A statistical difference was observed between immediate and delayed task for glaucoma patient on peak velocity ($F_{(1, 14)}$ = 6.04; p = 0.032; η^2 = 0.07) and acceleration interval ($F_{(1, 14)}$ = 4,87; p = 0.05; η^2 = 0.023). Glaucoma patient had faster peak velocity in delayed task (X_{mean} = 39.2 cm/s; SD = 11.7 cm/s) than in immediate task (X_{mean} = 32.4 cm/s; SD = 10.2 cm/s). Glaucoma patient had longer acceleration interval in delayed task (X_{mean} = 390.8 ms; SD = 100.6 ms) than in immediate task (X_{mean} = 358.4 ms; SD = 107 ms).

Discussion

The present study was designed to investigate whether abnormalities in reach-and-grasp tasks observed in previous studies in glaucoma patients resulted from difficulties in the perception of the relevant metric parameters to reach and grasp a target object (immediate condition: no time for visual exploration) or in motor production (delayed condition: time for visual exploration). Glaucoma patients and age-matched participants differed significantly in movement duration and peak velocity when participants had a temporal constraint for visual exploration (immediate condition). Glaucoma patients exhibited faster peak velocity, which is related to the reaching phase of the motor action execution.[29,30] Comparison of the immediate condition (X_{mean} = 32.4 cm/s; SD = 10.2 cm/s) versus the delayed condition (X_{mean} = 39.2 cm/s; SD = 11.7 cm/s) for each glaucoma patient confirm statistical difference on peak velocity. Moreover, a positive correlation was found for the immediate condition between the visual acuity of glaucoma patients and both movement duration and deceleration interval for all angles and time to MGA at 60° left angle. These results are consistent with previous studies showing a longer movement duration and correlations between visual acuity and both movement duration and peak velocity in glaucoma patients.[20] However, Kotecha and al. (2009) reported a negative correlation between visual acuity and peak velocity. One explanation could be that the participants' strategy consists in faster peak velocity to avoid the

441 acceleration interval (and movement duration) as “normal”. Consistent with this explanation,
442 we found no difference in terms of acceleration interval between glaucoma patients and age-
443 matched participants, unlike Kotecha et al. (2009). Methodological differences could account
444 for this change in strategy. In our study, the cylinders had the same size (5.5 cm) and
445 locations (25 cm) from the starting point at 0 (center), 30° and 60° to the left and to the right
446 of the central cylinder. In the studies by Kotecha et al., the cylinder changed in size (24 or 48
447 mm) and spatial location (200 mm or 400 mm) at each trial. Therefore, in their study, the
448 participants had to adjust the maximum opening of their hand to the size of the object,
449 whereas this adaptation was not required in our study because all cylinders had the same size
450 and distance. Participants can use the “same” motor command to adjust their maximum grip
451 aperture at each trial.[22,23] Interestingly, peak velocity differed between glaucoma patients and
452 age-matched participants, especially at 60° eccentricity left and right. Even though the
453 participants were in a natural situation where they could move their head freely, the deficit in
454 the peripheral visual field of glaucoma patients affected their kinematic parameters, especially
455 for an object located in the peripheral visual field.

456 As mentioned in the introduction, two interpretations might account for these
457 differences: (1) the kinematic difference of patients’ motor execution might result from the
458 effect of visual impairment on motor production; or (2) the effect of visual impairment on
459 identification (i.e., the spatial location and/or the width of the target) might lead to a motor
460 deficit. To dissociate these hypotheses, a second task (the delayed condition) was proposed to
461 the same participants. In this task, participants had time to explore and identify the target and
462 the distractors before reaching and grasping the target. In the delayed condition, a significant
463 difference was found in kinematic parameters between glaucoma patients and aging controls.
464 These deficits were found in deceleration intervals, which correspond to the grasp phase and
465 online control of action.[20,31,32] These result became clear in the light of the comparison

between the performance in the immediate condition versus the delayed condition for each glaucoma patient. The comparison revealed no statistical difference for the deceleration interval (Xmean = 860.4 ; SD = 230 ms for immediate condition and Xmean = 860.4 ms; SD = 162.8 ms for delayed condition). Hence, time to exploration is not helpful for glaucoma patient. The difference in the delayed condition on deceleration interval between glaucoma patient (Xmean = 860.4 ms; SD = 162.8 ms) and age-matched participant (Xmean = 651.6 ms; SD = 138 ms) results from increase performance (i.e. faster deceleration interval) for age-matched participant between the delayed condition (Xmean = 651.6 ms; SD = 138 ms) and the immediate condition (Xmean = 760.4 ms; SD = 139 ms) indicating that time to visual exploration is helpful for age-matched participant but not for glaucoma patient.

Like patients with AMD,[25] glaucoma patients exhibited motor deficit only when they had no time to explore the visual scene (immediate condition). The deficit is specific to the reach phase. The motor abnormalities in reaching phase observed in glaucoma patient in previous studies seem to result from difficulties in target identification rather than from visuo-motor deficits. Further studies are needed in binocular viewing conditions with various natural objects to confirm and clarify these results and extend them to daily life activities.

Conclusion and limitations

Glaucoma patients exhibited a motor disorder (reaching phase) in our study, only when they had no time to explore their environment before performing the reach-and-grasp task. From a clinical point of view, motor performance of glaucoma patients could be modulated by task, especially by temporal constraints of task.

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Figure Legends

Figure 1. Schematic representation of experimental design. R = Red ; B = Blue ; Y = Yellow ; G = Green ; W = White.

Figure 2. Schematic representation of both tasks. The major difference is the separation of the visual exploration phase and the reach-and-grasp phase in the task, with no temporal constraint for visual exploration compared to mixing these two phases (visual exploration and reach-and-grasp) in the task with temporal constraints for visual exploration.

Figure 3. Plot of thumb and object velocity (left axis, dashed line) and grip aperture (right axis, solid line) versus time for one trial of immediate condition. MGA: Maximum Grip Aperture.

Figure 4. Peak velocity in function of angle for glaucoma patients (square), age-matched (diamond) and young participants (round) for immediate condition. Bars correspond to standard error.

Figure 5. Mean deceleration interval (all angles) in function of visual acuity (left panel) and MD 30-2 for tested eyes (right panel) for glaucoma patients.

Table 1

	Glaucoma patient	Age-matched	Young Control
Age	62.9 (7.74)	62.1 (10.4)	25.9 (4.09)
Gender	10 female	11 female	13 female
Tested eye	7 right	7 right	11 right
MD 30-2	-16.4 (5.76)	NA	NA
VA LogMAR	0.11 (0.09)	NA	NA
MMSE	28.6 (1.46)	28.9 (0.73)	29.7 (0.461)

Table 1. Demographic data of glaucoma patients, age-matched controls and young control participants. Standard deviation indicated between brackets. Aged-matched had VA ranging from 20/25 to 20/20.

Table 2

Number/Age/ Gender	MMSE	Tested Eye	VA LogMAR	MD 30-2 (tested eye)	MD 30-2
1/62/F	30	RE	0	-21.9	-26.17
2/67/F	28	RE	0.1	-8.6	-9.1
3/74/F	28	RE	0.1	-22.5	-22.8
4/62/F	30	RE	0.1	-9.1	-26.5
5/60/F	30	RE	0	-16.2	-11.2
6/60/M	30	RE	0.2	-16.1	-8.6
7/46/M	28	RE	0.1	-15.6	-17.4
8/69/F	29	LE	0.1	-9.04	-10.9
9/74/F	25	LE	0.1	-20	-17.5
10/62/F	29	LE	0.2	-16.1	-20.6
11/68/F	29	LE	0.2	-9.8	-14.5
12/67/F	26	LE	0	-15.4	-11.2
13/59/M	30	LE	0	-25.6	-28.9
14/68/M	29	LE	0.2	-27	-27.4
15/59/M	28	LE	0.3	-14.1	-17.8
16/49/M	28	LE	0	-15.3	-17.6

Table 2. Demographic and clinical data of patients with glaucoma. LE = left eye, RE = right eye, MMSE = Mini-mental state examination.

Table 3

	60° left	30° left	0°	30° right	60° right
Movement duration	**0.78**	0.46	**0.64**	**0.53**	**0.59**
Peak Velocity	0.3	0.07	0.01	0.05	0.145
Acceleration interval	0.4	0.08	0.15	0.02	0.34
Deceleration interval	**0.8**	**0.58**	**0.57**	**0.6**	**0.57**
MGA	0.02	0.12	0.11	0.13	0,03
Time to MGA	**0.7**	0.39	0.36	0.23	0.16

Table 3. Spearman correlations between visual acuity and each kinematic parameter in immediate condition for glaucoma patients. Correlations in bold are statistically significative. MGA = Maximum grip aperture.

Table 4

	Mouvement Duration in ms	**Peak velocity in cm/s**	Acceleration interval in ms	Deceleration interval in ms	MGA in mm	Time to MGA in ms
Glaucoma patient	1179 (250)	32.4 (10.2)	358.4 (107)	860.4 (230)	8,96 (1.82)	716,4 (191)
Age-matched	1001,8 (169.6)	24.4 (7.4)	378.2 (82.7)	760,4 (139)	8,88 (1.04)	665,4 (98.02)
Young control	680.2 (106.5)	22.8 (2.4)	269.4 (55)	458.6 (129.8)	9.47 (1.09)	463.6 (102.1)
Group effect	**p < 0.001***	**p < 0.001***	**p < 0.01**	**p < 0.001**	p = 0.28	**p < 0.001**
Group *Angle effect	**p = 0.013+**	**p = 0.032***	p = 0.59	**p < 0.001**	**P = 0.03**	p = 0.45

Table 4. For each kinematic parameter, mean and standard deviation for glaucoma patients, age-matched and young participants with statistical results as a function of Group and of Angle*Group in the immediate condition. Significant effects are in bold font. * indicates difference between glaucoma patients and age-matched participants in post-hoc test ($p < 0.05$). + indicates tendential difference between glaucoma patients and age-matched participants in post-hoc test ($p < 0.1$). ms: millisecond, mm: millimeter, cm/s: centimeter per second.

Table 5

	Mouvement Duration in ms	Peak velocity in cm/s	Acceleration Interval in ms	**Deceleration interval in ms**	MGA in mm	Time to MGA in ms
Glaucoma patient	1251.4 (242,2	39.2 (11.7)	390.8 (100.6)	860.4 (162.8)	8.7 (1.4)	804.2 (253.2)
Age-matched	1066 (175)	40.1 (10.7)	413 (109.6)	651.6 (138)	8.8 (1)	727 (148)
Young control	716 (110.8)	32.9 (5.3)	327 (42.1)	389.4 (95.7)	9.6 (1)	496.8 (86.1)
Group effect	**p < 0.001***	**p = 0.01**	**p = 0.005**	**p < 0.001***	**p = 0.04**	**p < 0.001**
Group *Angle effect	**p = 0.004**	p = 0.097	**p = 0.001**	p = 0.103	p = 0.13	p = 0.6

Table 5. For each kinematic parameter, mean and standard deviation for glaucoma patients, age-matched and young participants with statistical results as a function of Group and of Angle*Group in the delayed condition. Significant effects are in bold font. * indicates difference between glaucoma patients and age-matched participants in post-hoc test ($p < 0.05$). ms: millisecond, mm: millimeter, cm/s: centimeter per second.

Figure 1

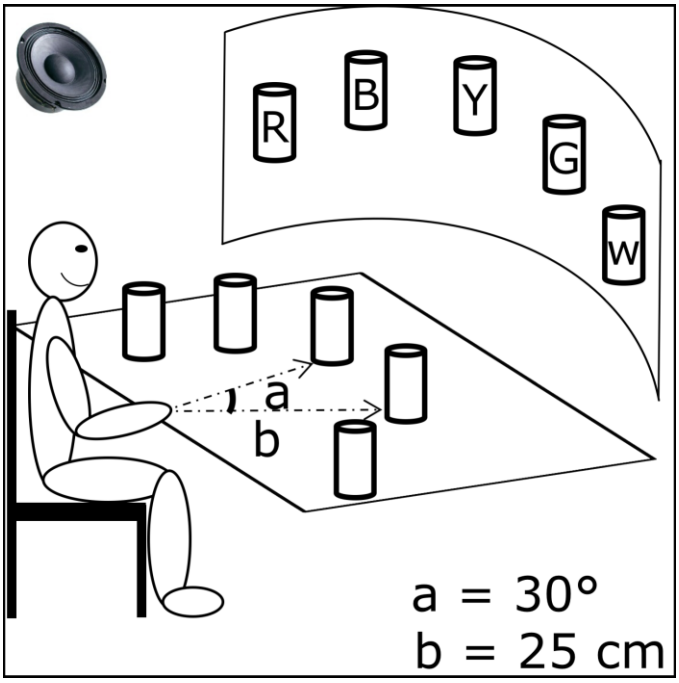
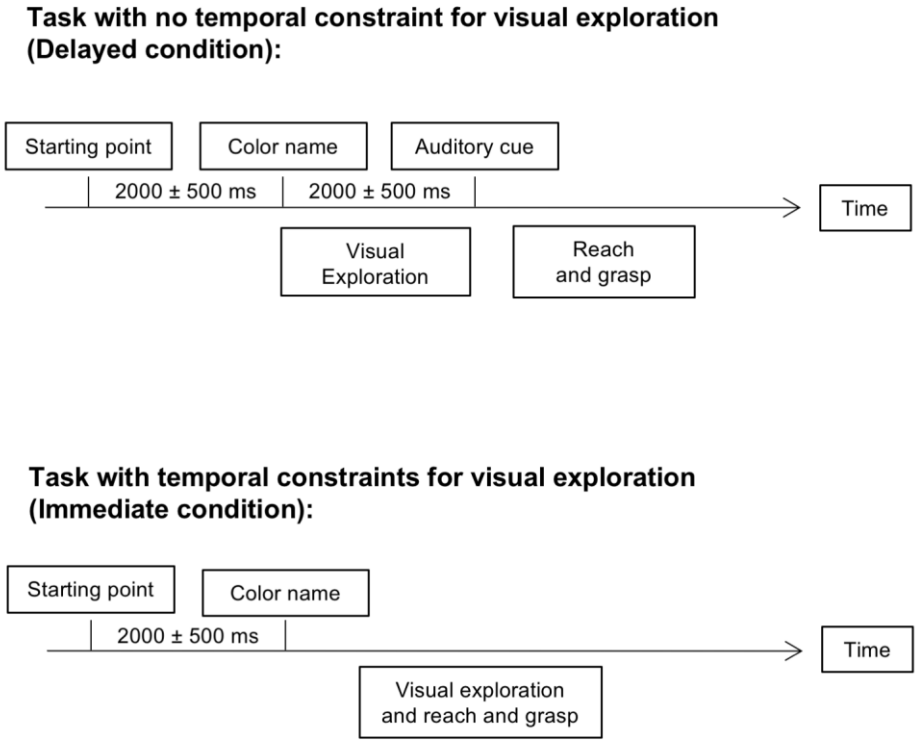


Figure 2


Task with no temporal constraint for visual exploration (Delayed condition):
Starting point
Color name
Auditory cue
2000 ± 500 ms
2000 ± 500 ms
Time
Visual Exploration
Reach and grasp
Task with temporal constraints for visual exploration (Immediate condition):
Starting point
Color name
2000 ± 500 ms
Time
Visual exploration and reach and grasp