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**What is the nature of the reach-and-grasp deficit in glaucoma?**

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32 **Précis**

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

36

37 **Abstract**

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

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

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

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

53

54 **Key Words**

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

56

## 57    **Introduction**

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

80 were found when healthy participants performed reach-and-grasp tasks with an artificially  
81 reduced visual field: longer overall movement duration, slower maximum velocity and higher  
82 maximum grip aperture.<sup>7</sup>

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

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

122

## 123 **Methods**

### 124 *Participants*

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

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

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

143

144 */ Insert table 1 here /*

145 */ Insert table 2 here /*

146

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

154

155 *Apparatus and material*

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

172

173 */Insert figure 1 here /*

174

175 */Insert figure 2 here /*

176

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

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

188

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



205

## 206 **Data Recording and Analysis**

207 A magnetic tracking system (Polhemus Liberty 240/8-8 System, Colchester, VT) was  
208 used to record the participants' movements in a X, Y and Z coordinates system. The  
209 kinematics of the reach-and-grasp movements and cylinder displacements were measured by  
210 eight markers that were placed on the index (base and tip), the thumb (tip), and the wrist  
211 (scaphoid and pisiform) of the participants. One additional marker was placed on each of the  
212 five cylinders. The spatial environment (table and cylinder) was calibrated before each  
213 session, allowing the system to reach a temporal and spatial resolution accuracy lower than  
214 0.2 mm at a 240 Hz sampling rate.

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

223

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

- 226 1. "Movement duration" corresponding to the time between movement onset and  
227 movement end (defined as the moment when participants reached the cylinder).
- 228 2. "Peak velocity" corresponding to the maximum velocity reached by the wrist during  
229 movement.

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

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

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

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

238

239 */Insert figure 3 here /*

240

241 Trials were excluded from the data analysis when a participant responded erroneously.  
242 1.6% of the trials, homogenously distributed across the conditions, were discarded. For each  
243 task, a 2x3 analysis of variance was conducted with each group {Glaucoma patients; Age-  
244 matched Controls; Young Controls} as the between-participants factor and angle condition  
245 {0°; 30° right; 30° left; 60° right; 60° left} as the within-participants factor. Local  
246 comparisons were performed using a post-hoc Bonferroni test with threshold corrections, in  
247 order to account for multiple group factor comparisons and possible interactions between  
248 Group and Angle. For the sake of clarity, principal effect of angle and post-hoc are not  
249 presented because we had no hypothesis on this factor. Spearman correlations for glaucoma  
250 patients were computed between each kinematic parameter, visual acuity, MD 30-2 and  
251 duration of pathology. Finally, comparisons of the results of the immediate condition vs  
252 delayed condition for each glaucoma patient were conducted. Results are presented in Tables  
253 3, 4 and 5.

254

255           **Results**

256

257           *Task with temporal constraints for visual exploration (immediate condition)*

258    1. *Movement duration*

259           A group effect was observed on movement durations ( $F_{(2, 45)} = 36.5$ ;  $p < 0.001$ ;  $\eta^2 =$   
260 0.6). The movement duration of glaucoma patients ( $X_{\text{mean}} = 1179$  ms;  $SD = 250$  ms) was  
261 significantly longer than that of age-matched participants ( $X_{\text{mean}} = 1001.8$  ms;  $SD = 169.6$  ms;  
262  $p < 0.014$ ) and young participants ( $X_{\text{mean}} = 680.2$  ms;  $SD = 106.5$  ms;  $p < 0.001$ ). The  
263 movement duration of age-matched participants was significantly longer than that of young  
264 participants ( $p < 0.001$ ).

265

266    2. *Peak velocity*

267           A group effect was observed on peak velocity ( $F_{(2, 45)} = 11.6$ ;  $p < 0.001$ ;  $\eta^2 = 0.27$ ).  
268 Peak velocity of glaucoma patients ( $X_{\text{mean}} = 32.4$  cm/s;  $SD = 10.2$  cm/s) was significantly  
269 faster than peak velocity of age-matched participants ( $X_{\text{mean}} = 24.4$  cm/s;  $SD = 7.4$  cm/s;  $p =$   
270 0.002) and young participants ( $X_{\text{mean}} = 22.8$  cm/s;  $SD = 2.4$  cm/s;  $p < 0.001$ ). No significant  
271 difference was found between age-matched and young participants.

272

273           An interaction was found between group and angle on peak velocity ( $F_{(8, 180)} = 2.17$ ;  $p$   
274  $= 0.032$ ;  $\eta^2 = 0.016$ ; Figure 4). The Bonferroni post-hoc comparison revealed that peak  
275 velocity for glaucoma patients was faster than peak velocity for age-matched participants and  
276 young participants, only at 60° eccentricity on the left (respectively  $p = 0.05$  and  $p = 0.002$ )  
277 and right angles (respectively  $p = 0.007$  and  $p < 0.001$ ).

278

279

*/ Insert figure 4 here /*

280

### 281 *3. Acceleration interval*

282 A group effect was observed on the acceleration interval ( $F_{(2, 45)} = 12.7$ ;  $p < 0.001$ ;  $\eta^2 =$   
283  $0.27$ ). The acceleration interval of glaucoma patients ( $X_{\text{mean}} = 358.4$  ms;  $SD = 107$  ms;  $p <$   
284  $0.001$ ) and age-matched participants ( $X_{\text{mean}} = 378.2$  ms;  $SD = 82.7$  ms;  $p < 0.001$ ) was  
285 significantly longer than that of young participants ( $X_{\text{mean}} = 269.4$  ms;  $SD = 55$  ms).

286

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

288

### 289 *4. Deceleration interval*

290 A group effect was observed on the deceleration interval ( $F_{(2, 45)} = 28$ ;  $p < 0.001$ ;  $\eta^2 =$   
291  $0.52$ ). No difference was observed between glaucoma patients and age-matched participants.  
292 The deceleration interval of both glaucoma patients ( $X_{\text{mean}} = 860.4$  ms;  $SD = 230$  ms;  $p <$   
293  $0.001$ ) and age-matched participants ( $X_{\text{mean}} = 760.4$  ms;  $SD = 139$  ms;  $p < 0.001$ ) was  
294 significantly longer than that of young participants ( $X_{\text{mean}} = 458.6$  ms;  $SD = 129.8$  ms).

295

296 An interaction was found between group and angle on the deceleration interval ( $F_{(8, 180)}$   
297  $= 4.53$ ;  $p < 0.001$ ;  $\eta^2 = 0.014$ ). The Bonferroni post-hoc comparison revealed differences for  
298 glaucoma patients and age-matched participants in comparison to young participants ( $p <$   
299  $0.001$ ) for all angles (except young versus age-matched participants for  $60^\circ$  right ( $p = 0.02$ )  
300 and  $60^\circ$  left ( $p = 0.003$ )).

301

302 *5. Maximum grip aperture*

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

307

308 An interaction was found between group and angle on maximum grip aperture ( $F_{(8, 180)}$   
309  $= 1.21$ ;  $p = 0.03$ ;  $\eta^2 = 0.017$ ). The Bonferroni post-hoc comparison revealed a difference  
310 between  $60^\circ$  right ( $X_{\text{mean}} = 8.62$  cm;  $SD = 2.38$  cm) and  $60^\circ$  left ( $X_{\text{mean}} = 9.31$  cm;  $SD = 1.87$   
311 cm) for glaucoma patients only ( $p = 0.034$ ).

312

313 *6. Time to maximum grip aperture*

314 A group effect was observed on time to maximum grip aperture ( $F_{(2, 45)} = 23.7$ ;  $p <$   
315  $0.001$ ;  $\eta^2 = 0.42$ ). The time to maximum grip aperture of glaucoma patients ( $X_{\text{mean}} = 716.4$  ms;  
316  $SD = 191$  ms;  $p < 0.001$ ) and age-matched participants ( $X_{\text{mean}} = 665.4$ ;  $SD = 98$  cm;  $p > 0.001$ )  
317 was significantly shorter than that of young participants ( $X_{\text{mean}} = 463.6$  cm;  $SD = 102.1$  cm).

318

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

320

321 */ Insert Table 3 here /*

322

323 Finally, correlations were found between visual acuity for glaucoma patients and  
324 movement duration, deceleration interval and time to MGA (for  $60^\circ$  left condition only),

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

327

328 */ Insert Figure 5 here /*

329

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

336

337 */Insert Table 4 here /*

338 */Insert Table 5 here /*

339

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

##### 341 *1. Movement duration*

342 A group effect was observed on movement durations ( $F_{(2, 45)} = 41.4; p < 0.001; \eta^2 =$   
343  $0.63$ ). The movement duration of glaucoma patients ( $X_{\text{mean}} = 1251.4$  ms;  $SD = 242.2$  ms) was  
344 significantly longer than that of age-matched participants ( $X_{\text{mean}} = 1066$  ms;  $SD = 175$  ms;  $p =$   
345  $0.02$ ) and young participants ( $X_{\text{mean}} = 716$  ms;  $SD = 110.8$  ms;  $p < 0.001$ ). The movement  
346 duration of age-matched participants was significantly longer than that of young participants,  
347  $p < 0.001$ )

348

349 An interaction was found between Group and Angle on movement duration ( $F_{(8, 180)} =$   
350  $2.99$ ;  $p = 0.004$ ;  $\eta^2 = 0.006$ ). No significant differences were observed between the movement  
351 duration of glaucoma patients and age-matched participants for all angles. The movement  
352 duration of glaucoma patients and age-matched participants was significantly longer than that  
353 of young participants ( $p < 0.01$  for all angles, except age-matched versus young participants at  
354  $60^\circ$  left ( $p = 0.007$ )).

355

### 356 *2. Peak velocity*

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

361

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

363

### 364 *3. Acceleration interval*

365 A group effect was observed on the acceleration interval ( $F_{(2, 45)} = 6.03$ ;  $p = 0.005$ ;  $\eta^2 =$   
366  $0.157$ ). The acceleration interval of glaucoma patients ( $X_{\text{mean}} = 390.8$  ms;  $SD = 100.6$  ms;  $p =$   
367  $0.06$  (trend)) and age-matched participants ( $X_{\text{mean}} = 413$  ms;  $SD = 109.6$  ms;  $p = 0.006$ ) was  
368 significantly longer than that of young participants ( $X_{\text{mean}} = 327$  ms;  $SD = 42.1$  ms).

369

370 An interaction was found between group and angle on acceleration intervals ( $F_{(8, 180)} =$   
371  $3.34$ ;  $p = 0.001$ ;  $\eta^2 = 0.036$ ). The Bonferroni post-hoc comparison revealed a difference  
372 between age-matched and young participants at  $30^\circ$  left angle ( $p = 0.004$ ).

373

#### 374 *4. Deceleration interval*

375 A group effect was observed on the deceleration interval ( $F_{(2, 45)} = 59.2$ ;  $p < 0.001$ ;  $\eta^2 =$   
376  $0.704$ ). The deceleration interval of glaucoma patients ( $X_{\text{mean}} = 860.4$  ms;  $SD = 162.8$  ms;  $p <$   
377  $0.001$ ) was longer than that of age-matched participants ( $X_{\text{mean}} = 651.6$  ms;  $SD = 138$  ms;  $p <$   
378  $0.001$ ) and young participants ( $X_{\text{mean}} = 389.4$  ms;  $SD = 95.7$  ms). The deceleration interval of  
379 age-matched participants was longer than that of young participants ( $p < 0.001$ ).

380

381 No interaction was observed between group and angle.

382

#### 383 *5. Maximum grip aperture*

384 A group effect was observed on maximum grip aperture ( $F_{(2, 45)} = 3.5$ ;  $p < 0.04$ ;  $\eta^2 =$   
385  $0.13$ ). The maximum grip aperture of glaucoma patients ( $X_{\text{mean}} = 8.7$  cm;  $SD = 1.4$  cm) was  
386 not significantly different from that of age-matched participants ( $X_{\text{mean}} = 8.8$  cm;  $SD = 1$  cm).  
387 A tendency was observed between the maximum grip aperture of glaucoma patients and that  
388 of young participants ( $p = 0.079$ ). ( $X_{\text{mean}} = 9.6$  cm;  $SD = 1$  cm,  $p = 0.08$ ).

389

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

391

#### 392 *6. Time to maximum grip aperture*



393 A group effect was observed on time to maximum grip aperture ( $F_{(2, 45)} = 19.2$ ;  $p <$   
394  $0.001$ ;  $\eta^2 = 0.29$ ). A Bonferroni post-hoc comparison revealed a significant interaction  
395 between the time to maximum grip aperture of both glaucoma patients ( $X_{\text{mean}} = 804.2$  ms; SD  
396  $= 253.2$  ms) and age-matched participants ( $X_{\text{mean}} = 727$ ; SD  $= 148$  cm) with young  
397 participants ( $X_{\text{mean}} = 496.8$  cm; SD  $= 86.1$  cm,  $p < 0.001$ ).

398

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

400

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

403

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

409

410 *Comparison between the immediate versus delayed conditions for each glaucoma*  
411 *patient*

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

415

416 A statistical difference was observed between immediate and delayed task for  
417 glaucoma patient on peak velocity ( $F_{(1, 14)} = 6.04$ ;  $p = 0.032$ ;  $\eta^2 = 0.07$ ) and acceleration  
418 interval ( $F_{(1, 14)} = 4.87$ ;  $p = 0.05$ ;  $\eta^2 = 0.023$ ). Glaucoma patient had faster peak velocity in  
419 delayed task ( $X_{\text{mean}} = 39.2$  cm/s;  $SD = 11.7$  cm/s) than in immediate task ( $X_{\text{mean}} = 32.4$  cm/s;  
420  $SD = 10.2$  cm/s). Glaucoma patient had longer acceleration interval in delayed task ( $X_{\text{mean}} =$   
421  $390.8$  ms;  $SD = 100.6$  ms) than in immediate task ( $X_{\text{mean}} = 358.4$  ms;  $SD = 107$  ms).

422

## 423 **Discussion**

424 The present study was designed to investigate whether abnormalities in reach-and-  
425 grasp tasks observed in previous studies in glaucoma patients resulted from difficulties in the  
426 perception of the relevant metric parameters to reach and grasp a target object (immediate  
427 condition: no time for visual exploration) or in motor production (delayed condition: time for  
428 visual exploration). Glaucoma patients and age-matched participants differed significantly in  
429 movement duration and peak velocity when participants had a temporal constraint for visual  
430 exploration (immediate condition). Glaucoma patients exhibited faster peak velocity, which is  
431 related to the reaching phase of the motor action execution.<sup>29,30</sup> Comparison of the immediate  
432 condition ( $X_{\text{mean}} = 32.4$  cm/s;  $SD = 10.2$  cm/s) versus the delayed condition ( $X_{\text{mean}} = 39.2$   
433 cm/s;  $SD = 11.7$  cm/s) for each glaucoma patient confirm statistical difference on peak  
434 velocity. Moreover, a positive correlation was found for the immediate condition between the  
435 visual acuity of glaucoma patients and both movement duration and deceleration interval for  
436 all angles and time to MGA at 60° left angle. These results are consistent with previous  
437 studies showing a longer movement duration and correlations between visual acuity and both  
438 movement duration and peak velocity in glaucoma patients.<sup>20</sup> However, Kotecha and al.  
439 (2009) reported a negative correlation between visual acuity and peak velocity. One  
440 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.<sup>22,23</sup> 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.<sup>20,31,32</sup> These result became clear in the light of the comparison

466 between the performance in the immediate condition versus the delayed condition for each  
467 glaucoma patient. The comparison revealed no statistical difference for the deceleration  
468 interval ( $X_{\text{mean}} = 860.4$  ;  $SD = 230$  ms for immediate condition and  $X_{\text{mean}} = 860.4$  ms;  $SD$   
469  $= 162.8$  ms for delayed condition). Hence, time to exploration is not helpful for glaucoma  
470 patient. The difference in the delayed condition on deceleration interval between glaucoma  
471 patient ( $X_{\text{mean}} = 860.4$  ms;  $SD = 162.8$  ms) and age-matched participant ( $X_{\text{mean}} = 651.6$   
472 ms;  $SD = 138$  ms) results from increase performance (i.e. faster deceleration interval) for  
473 age-matched participant between the delayed condition ( $X_{\text{mean}} = 651.6$  ms;  $SD = 138$  ms)  
474 and the immediate condition ( $X_{\text{mean}} = 760.4$  ms;  $SD = 139$  ms) indicating that time to visual  
475 exploration is helpful for age-matched participant but not for glaucoma patient.

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

482

### 483 **Conclusion and limitations**

484 Glaucoma patients exhibited a motor disorder (reaching phase) in our study, only  
485 when they had no time to explore their environment before performing the reach-and-grasp  
486 task. From a clinical point of view, motor performance of glaucoma patients could be  
487 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	<b>0.78</b>	0.46	<b>0.64</b>	<b>0.53</b>	<b>0.59</b>
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	<b>0.8</b>	<b>0.58</b>	<b>0.57</b>	<b>0.6</b>	<b>0.57</b>
MGA	0.02	0.12	0.11	0.13	0,03
Time to MGA	<b>0.7</b>	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 significant.

MGA = Maximum grip aperture.

Table 4

	<b>Mouvement Duration in ms</b>	<b>Peak velocity in cm/s</b>	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	<b>p &lt; 0.001*</b>	<b>p &lt; 0.001*</b>	<b>p &lt; 0.01</b>	<b>p &lt; 0.001</b>	p = 0.28	<b>p &lt; 0.001</b>
Group *Angle effect	<b>p = 0.013+</b>	<b>p = 0.032*</b>	p = 0.59	<b>p &lt; 0.001</b>	<b>P = 0.03</b>	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

	<b>Mouvement Duration in ms</b>	Peak velocity in cm/s	Acceleration Interval in ms	<b>Deceleration interval in ms</b>	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	<b>p &lt; 0.001*</b>	<b>p = 0.01</b>	<b>p = 0.005</b>	<b>p &lt; 0.001*</b>	<b>p = 0.04</b>	<b>p &lt; 0.001</b>
Group *Angle effect	<b>p = 0.004</b>	p = 0.097	<b>p = 0.001</b>	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

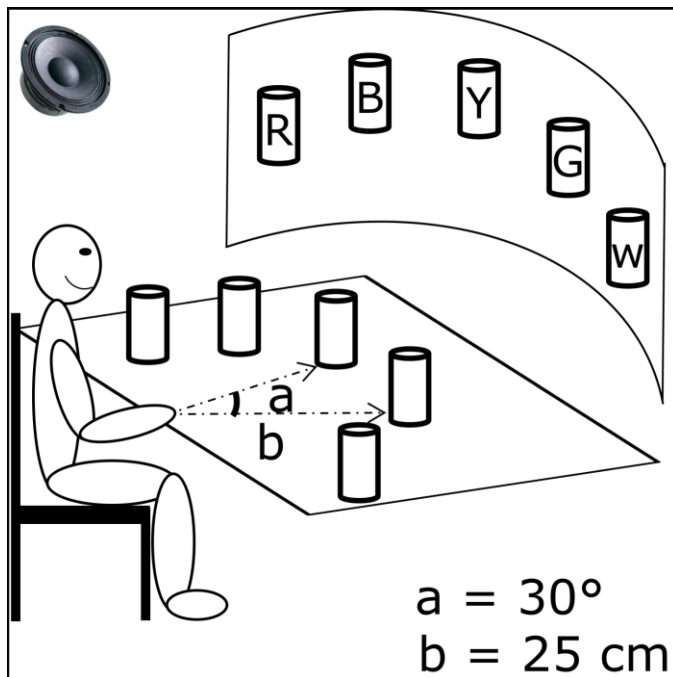
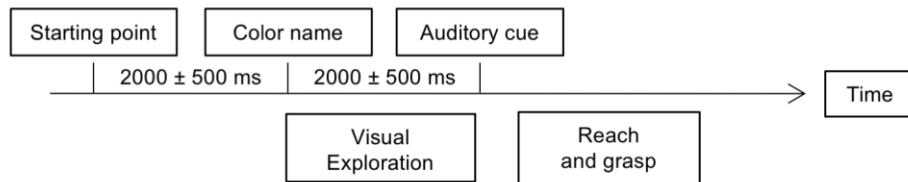


Figure 2

**Task with no temporal constraint for visual exploration  
(Delayed condition):**



**Task with temporal constraints for visual exploration  
(Immediate condition):**

