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Higher susceptibility to central crowding in glaucoma

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30 **Abstract**

31 **Clinical relevance:** Crowding limits many daily life activities, such as reading and the visual
32 search for objects in cluttered environments. Excessive sensitivity to crowding, especially in
33 central vision, may amplify the difficulties of patients with ocular pathologies. It is thus
34 important to investigate what limits visual activities and how to improve it.

35

36 **Background:** Numerous studies have reported reduced contrast sensitivity in central vision in
37 patients with glaucoma. However, deficits have also been observed for letter recognition at
38 high contrast, suggesting that contrast alone cannot completely account for impaired central
39 perception.

40 **Method:** Seventeen patients and fifteen age-matched controls were randomly presented with
41 letters in central or parafoveal vision at 5° eccentricity for 200 ms. They were asked to decide
42 whether the central T was upright or inverted. The T was either presented in isolation
43 (uncrowded) or flanked by two Hs (crowded) at various spacings. Contrast was manipulated:
44 60% and 5%.

45 **Results:** Compared to controls, patients exhibited a significant effect of crowding in central
46 vision, with higher accuracy for the isolated T than for HTH only at low contrast. In
47 parafoveal vision, an effect of crowding was also observed only in patients. The spacing to
48 escape crowding varied as a function of contrast. Larger spacing was required at low contrast
49 than at high contrast. Susceptibility to crowding was related to central visual field defect for
50 central presentations and to contrast sensitivity for parafoveal presentations, only at low
51 contrast. Controls were at ceiling level both for central and parafoveal presentations.

52 **Conclusion:** Crowding limits visual perception, impeding reading and object recognition in
53 cluttered environments. We demonstrate that visual field defect and lower contrast sensitivity
54 in glaucoma can increase susceptibility to central and parafoveal crowding, the deleterious
55 effect of which can be improved by manipulating contrast and spacing between elements.

56

57 **Key words:** glaucoma, crowding, contrast, central vision, parafoveal vision.

58

59

60 **Introduction**

61 Glaucoma is a chronic ocular pathology characterized by degeneration of optic nerve
62 fibers and apoptosis of retinal ganglion cells. This results in scotoma starting in the peripheral
63 visual field and progressing towards the central field. Glaucoma was long believed to spare
64 central vision until an advanced stage, but evidence is growing that patients experience
65 difficulties or deficits in activities reliant on central vision, such as reading,¹⁻³ visual search⁴⁻⁵
66 and face recognition.⁶⁻⁸ The mechanisms underlying impairments in central vision are not yet
67 completely understood. Several psychophysical studies have shown evidence of abnormal
68 foveal contrast sensitivity in glaucoma.⁹⁻¹¹ Reduced contrast sensitivity in central vision
69 affects reading. Increasing contrast from 10% to 50% has been found to be associated with
70 significant improvement in reading speed in patients with glaucoma at various stages of the
71 disease, whilst font size and line spacing had no effect on reading speed in that study.¹² This
72 result indicates that reduced contrast sensitivity is a critical factor for slower reading in
73 glaucoma. However, contrast alone cannot completely account for abnormalities in central
74 vision. Indeed, with random strings of three letters presented centrally for 200 ms with a
75 contrast of 99%, Kwon et al.³ found lower accuracy in the identification of centrally displayed
76 letters in glaucomatous patients than in normally sighted participants. This result was
77 interpreted as a shrinkage of the visual span in glaucoma. Stievenard et al.¹³ investigated
78 foveal face perception in patients with glaucoma. Performance was compared for the
79 categorization of a facial feature: closed mouth vs. open mouth, presented in isolation vs. in
80 the context of a face. Normally sighted participants exhibited a “face superiority effect” with a
81 better performance in the “mouth within a face” condition than in the “isolated mouth”
82 condition. However, patients with glaucoma exhibited a better performance in the “isolated
83 mouth” condition than in the “mouth within a face” condition. This was interpreted as a
84 higher susceptibility to crowding in central vision in glaucoma. Results also showed that
85 increasing the angular size of the face, and therefore the spacing between facial features,
86 reversed performance in patients who, like controls, exhibited a better performance in the
87 “mouth within a face” condition than in the “isolated mouth” condition for larger faces. These
88 two behavioral studies indicate that crowding may also be a critical factor of perceptual
89 deficit in foveal vision in glaucoma despite good visual acuity.

90 The present study explores how contrast and spacing together limit discriminability of a letter
91 among neighboring letters (flankers) in central vision. Patients with glaucoma and age-
92 matched controls were presented with letters displayed for 200 ms in fovea and parafovea.

93 Crowding was manipulated by the spacing between a central letter and its flankers (crowded
94 condition) and compared to an isolated letter (uncrowded condition). Performance was
95 measured at two levels of contrast (5% and 60%). In normally sighted people crowding is
96 usually observed in peripheral vision where spatial sensitivity is reduced whilst little
97 crowding exists in normal central/parafoveal vision.¹⁴⁻¹⁵ Based on previous studies suggesting
98 a higher susceptibility to crowding in foveal vision in glaucoma,^{3, 13} and a recent study
99 showing that crowding is exacerbated in parafoveal vision (2° and 4° eccentricity)¹⁶ in
100 glaucoma, crowding was expected to be more pronounced in patients than in controls.
101 Moreover, since previous studies had demonstrated altered contrast sensitivity in central
102 vision in glaucoma, a modulation of the effect of crowding by contrast was expected.

103

104 **Method**

105

106 **Participants**

107 Seventeen patients (11 females) with a visual field (VF) defect due to primary open-
108 angle glaucoma participated. They ranged from 47 to 74 years of age (mean: 65.5 years SD:
109 8.6). Each patient underwent a complete ophthalmological examination including a visual
110 field evaluation just before the experiment. Visual field sensitivity (expressed as the mean
111 deviation: MD) was measured with a central 10-2 strategy on the Humphrey Field Analyzer
112 SITA Standard (HFA II, Carl Zeiss Medical, CA, USA). We included patients with different
113 deviations at the 10-2 visual field to assess whether sensitivity to central crowding occurs
114 even at early stages of glaucoma. Visual acuity and contrast sensitivity were measured using
115 the Freiburg Vision Test (FrACT).

116 Fifteen age-matched controls (9 females) ranging from 53 to 78 years in age (mean:
117 61.9 years SD: 7.1) were recruited among the patients' relatives and staff of the
118 ophthalmology department. Inclusion criteria for both patients and controls were the
119 following: no history of neurological and/or psychiatric disease, no ocular disease other than
120 glaucoma for patients, and no family history of glaucoma for controls. Cataract was an
121 exclusion criterion. The characteristics of the two populations are summarized in Table 1.

122 Patients and controls were tested monocularly. Controls were tested on their preferred
123 eye. For patients with bilateral glaucoma, the tested eye was the one that met the inclusion
124 criteria: a deviation on the 10-2 visual field test and an acuity equal to or better than 8/10 (0.1

125 LogMAR). If both eyes were impaired at the 10-2, the better eye was chosen. The 10-2 visual
126 fields of the tested eyes are displayed in Figure 1.

127 For both groups, a binocular acuity lower than 8/10 (0.1 LogMar) was an exclusion
128 criterion. All participants were asked to attend with their usual optical correction. Older
129 patients and age-matched controls wore progressive spectacles for close and distant vision.
130 Patients and age-matched controls did not differ significantly in age ($t(30) = 1.28$, $p = 0.20$).
131 They differed marginally in acuity ($t(30) = 2.01$, $p < .053$) and contrast sensitivity was
132 significantly lower in patients than in controls (1.9 vs 1.63 $t(30) = 3.84$, $p < .001$). The study
133 was approved by the ethics committee for behavioral sciences of the University of Lille. In
134 accordance with the tenets of the Declaration of Helsinki, written informed consent was
135 obtained from all participants.

136 **[Table1 about here]**
137

138 **Stimuli and apparatus**

139 The stimuli were uppercase letters H and T, in Arial font, presented on a 15-inch
140 DELL computer screen. The target was the letter T, either oriented upright or inverted. The
141 flankers were the letter H positioned left and right of the target. The angular size of the letters
142 was 0.4° vertically and 0.3° horizontally at a viewing distance of 57 cm with a chin rest. Two
143 grey levels of luminance were selected for the stimuli (76 cd/m^2 and 103 cd/m^2). Presented on
144 a light gray background (luminance: 113 cd/m^2) the levels of contrast (Michelson) of the
145 stimuli were 60% and 5%.

147 **Procedure**

148 Each trial started with a central black fixation cross (0.5°) displayed for 500 ms. After
149 a 500-ms blank gap, the stimulus appeared randomly at three possible spatial locations (0°
150 central, 5° left, 5° right of fixation cross). The spatial locations -5 to $+5^\circ$ corresponds to the
151 size of the central visual span in Kwon et al.³ The paradigm is illustrated in Figure 2. A pilot
152 experiment conducted on five other patients (not included in the present experiment), with
153 stimuli displayed for 150 ms, showed that they were at chance on most trials. In the
154 experimental session, the duration of the stimuli was set at 200 ms. There was no control of
155 fixation as the fixation cross disappeared for 500 ms before the presentation of the stimulus to
156 avoid it masking a central stimulus. The fixation cross also disappeared for 500 ms before the

157 presentation of parafoveal stimuli to avoid the fixation marker serving as a cue that the
158 stimulus would appear in the parafoveal field.

159 Crowding was assessed (1) by manipulating the spacing between target and flankers
160 and (2) by comparing performance between the crowded conditions (target and flankers) and
161 a baseline uncrowded condition (isolated T). In the crowded condition there were three
162 spacings between target and flankers at 5° eccentricity. According to Bouma's law,¹⁷ the
163 critical spacing for identification of small letters is roughly half the eccentricity. The three
164 chosen spacings were 2.5° (half of 5°), 2° (below critical spacing) and 3° (above critical
165 spacing) edge-to-edge. For central stimuli, the spacings between target and flankers were 0
166 (no spacing) and 0.3° (corresponding to the width of a capital letter).

167 Target letter T, either isolated or flanked, was randomly presented upright in 50% of
168 the trials and inverted in the other 50%. Participants were asked to decide whether the letter T
169 was upright or inverted regardless of the presence of flankers. The response was given using
170 the arrow keys of the computer keyboard (pointing top for upright and bottom for inverted).
171 The inter-trial interval was set at 1500 ms after response.

172 The crowded and uncrowded conditions, the contrast of the stimuli (60%, 5%), the
173 spatial locations of the stimuli (left/right) and the orientation of the T were randomly
174 presented. The experimental session was composed of 440 trials determined by 120 central
175 trials (isolated T and two spacing conditions X two contrast conditions X 20 repetitions) and
176 320 parafoveal trials (isolated T and three spacing conditions X two contrast conditions X two
177 spatial locations X 20 repetitions). The 20 repetitions were 10 upright Ts and 10 inverted Ts.
178 A pause was proposed after 110, 220 and 330 trials. Participants resumed the experiment by
179 pressing the space bar of the keyboard. Following a training session of 20 trials, the
180 experimental session lasted 20-25 minutes depending on the response time of participants.

181

182

[Figure 1 about here]

183

184 **Statistical analysis**

185

186 As the number of spacing conditions was different for parafoveal and central presentations,
187 separate ANOVAs were carried out. As the percentage of correct responses is not linear
188 accuracy was converted to a Z-score for each group. Analyses were conducted on the Z-scores
189 using Systat 8 software (Systat Software, Inc. San Jose, California). Though the upright T was

190 detected more accurately than the inverted T the orientation of the T was not included as
191 factor in the analysis since the advantage of the upright T was observed for both groups
192 (patients $F(1, 16) = 18.9, p < .001$, controls $F(1, 14) = 17.7, p < .001$), for the two levels of
193 contrast, for foveal and parafoveal presentations and for crowded and isolated stimuli. The
194 analyses were therefore based on 20 measures/condition. Owing to significant inter-individual
195 variability, we did not analyze response times as some patients were fast (around 500 ms)
196 while others were very slow (above 3 sec). The group (patients/age-matched controls) was the
197 between-subject factor. The spatial location of the stimuli (left/right), contrast (60% and 5%)
198 and spacing between target and flankers were the within-subject factors. The relations
199 between clinical data (acuity, contrast sensitivity, visual field defect: MD), age and amplitude
200 of crowding were assessed using a Spearman correlation analysis.

201

202

[Figure 2 about here]

203

204 **Results**

205

206 **Central presentations**

207 The results are presented in Figure 3. Accuracy was higher for controls than for
208 patients ($F(1, 30) = 10.8, p < .003$). Performance was better in the high than in the low contrast
209 condition for both groups ($F(1, 30) = 12.5, p < .001$). A significant main effect of spacing was
210 observed ($F(2, 60) = 4.62, p < .014$). Although the interaction between group and spacing was
211 not significant ($F(2, 60) = 1.08, p = 0.35$), Figure 3 shows that the effect of spacing resulted
212 mainly from the patients' group ($F(2, 32) = 3.6, p < .039$) and not from the control group ($F(2,$
213 $28) = 2.3, p = 0.11$). A significant effect of crowding was observed for patients in the low
214 contrast condition, with a better performance for the isolated T than for the crowded condition
215 with no spacing (T vs. HTH: $t(16) = 3.63, p < .002$), but not between the isolated T and the
216 crowded condition with a larger spacing (T vs; H T H: $t(16) = 1.7, p = 0.11$). No significant
217 effect of crowding was found in the high contrast condition for patients. Age-matched
218 controls exhibited no statistically significant effect of crowding for central presentations even
219 for low contrast (T vs THT: $t(14) = 1.38, p = 0.18$). Individual data are presented in Figure 4
220 for patients at low contrast. The results show that 12 out of the 17 patients exhibited a better
221 performance for the isolated T than for the crowded condition with no spacing, four patients

222 had the same performance for both T and HTH, and patient 4 with the higher central field
223 defect was at chance for the isolated T and perceived the trigram of letters better.

224 **[Figures 3 and 4 about here]**

225 **Parafoveal presentations**

226 The results are presented in Figure 5. Accuracy was significantly higher in controls
227 than in patients ($F(1, 30) = 23.6, p < .001$). Performance was better for high than for low
228 contrast ($F(1, 30) = 26.9, p < .001$). There was no main effect of spatial location of the stimuli
229 (temporal: 80.1% vs. nasal: 79.3%, $F(1, 30) = 0.10, p = 0.74$), although it interacted
230 significantly with group ($F(1, 30) = 8.7, p < .006$). This interaction resulted from the patients
231 who exhibited a higher accuracy in the temporal than in the nasal field (by 8.3%, $F(1, 16) =$
232 $4.42, p < .05$). Examination of individual data showed that the higher accuracy in the temporal
233 field resulted from the five patients (P1, P4, P5, P9 and P12) with the greater alteration of the
234 visual field (Figure 1): temporal field 83.5% vs nasal field 62%. Performance was equivalent
235 in the temporal and the nasal fields (67.9% vs 66.5%) for the 12 other patients with a smaller
236 alteration of the visual field. On average, the spacing between target and flankers did not
237 affect accuracy ($F(3, 90) = 0.8, p = 0.49$), while it interacted significantly with group ($F(3, 90)$
238 $= 4.13, p < .009$) and contrast in a three-way interaction ($F(3, 90) = 3.33, p < .023$). The
239 interaction resulted from the patients' group. At high contrast their performance was
240 significantly better for the isolated T than for the T with flankers in the smaller spacing
241 condition ($t(16) = 2.53, p < .022$). At low contrast, accuracy was significantly higher with the
242 large spacing than with the medium spacing ($t(16) = 2.18, p < .045$). The comparison between
243 spacing conditions for controls revealed no statistically significant effect of spacing.

244 **[Figure 5 about here]**

245 **Correlations**

246 We used a Spearman measure of correlation between clinical measures (MD, contrast
247 sensitivity and acuity) and crowding. For foveal presentations, the effect of crowding (isolated
248 T minus HTH in the no spacing condition) at low contrast was significantly related to the
249 severity of the central visual field loss MD ($r = 0.671, p < .003$), but not to contrast sensitivity
250 ($r = 0.224, p = 0.387$) and acuity ($r = 0.132, p = 0.613$). For parafoveal presentations, the
251 lower performance for the crowded condition HTH with the medium spacing than with the
252 large spacing at low contrast was correlated with contrast sensitivity ($r = 0.506, p < .038$), but

253 not with MD ($r = 0.122$, $p = 0.638$) and acuity ($r = 0.20$, $p = 0.442$). Performance at high
254 contrast in parafoveal vision was not related to clinical variables: MD ($r = 0.205$, $p = 0.430$),
255 contrast sensitivity ($r = 0.226$, $p = 0.381$) and acuity ($r = 0.240$, $p = 0.352$). Contrast
256 sensitivity was significantly related to age in the patients' group ($r = 0.536$, $p < .026$).

257 **Discussion**

258 This study sought to investigate the mechanisms underlying impairments in central
259 vision in glaucoma. We were especially interested in testing whether the association of two
260 factors, crowding and contrast sensitivity, is responsible for impaired foveal and parafoveal
261 perception of letters. A significant effect of crowding was observed in central vision in 12 out
262 of the 17 patients at low contrast, but not at higher contrast, although a tendency was present.
263 No crowding was observed in controls who were at ceiling for both foveal and parafoveal
264 presentations. In parafoveal vision, the level of contrast modulated the target-to-flanker
265 distance for patients to perceive the central letter. Indeed, a larger target-to-flanker spacing
266 was required to escape crowding at low contrast (3°) than at higher contrast (2.5°). Accuracy
267 was significantly lower with a medium spacing (2.5°) than with a larger spacing (3°) at low
268 contrast, while the lowest accuracy was observed at a target-to-flanker distance of 2° at high
269 contrast. The issue of contrast dependency of crowding has been examined in several studies;
270 however, the contrast of target and flankers is usually manipulated asymmetrically with a
271 higher or lower contrast for target than for flankers. The results classically show that the
272 strength of crowding is related to the contrast of flankers: crowding is weak when the target is
273 of higher contrast than the flankers and strong when the contrast of flankers is higher than that
274 of the target.¹⁸⁻²⁰ However, a study in which the contrast was the same for both target and
275 flankers showed that the critical spacing between target and flankers decreased when the
276 contrast was reduced below approximately 24% in foveal vision and below 17% in peripheral
277 vision (at 3 to 10°) in five normally sighted observers.²¹ Contrast is also known to affect
278 reading in normally sighted individuals.²²⁻²⁴

279 The greater effect of crowding in parafoveal vision in patients than in controls is consistent
280 with the findings of previous studies who showed that glaucomatous damage was associated
281 with increased crowding in the parafoveal region (2 and 4°) and in peripheral vision (10°).^{16,}
282 ²⁵

283 In the present study, normally sighted age-matched controls did not exhibit the foveal
284 or parafoveal effect of crowding. Moreover, their mean accuracy was only 1% lower in
285 parafoveal than in foveal vision, while accuracy was 8.4% lower in parafoveal than in foveal

286 vision in patients. This result indicates that the task was too easy for controls, likely owing to
287 a too long presentation time (200 ms) and a too large target-to-flanker spacing.

288 Susceptibility to central crowding in patients was found to be related to central visual
289 field defect but not to contrast sensitivity. Patients' contrast sensitivity was measured in
290 foveal vision using the Freiburg Vision Test (Fract). In this test, contrast is measured at
291 threshold, at a viewing distance of 1m on the orientation of the small aperture in a C letter. In
292 the experimental session, stimuli were displayed above contrast threshold at a shorter viewing
293 distance. These easier viewing conditions may account for the absence of relation between
294 crowding and contrast sensitivity in foveal vision in patients.

295 Although there is no consensus regarding the mechanisms underlying crowding, there
296 is agreement on its cortical origin.²⁶⁻²⁸ Some authors have suggested V1 as the earliest source
297 of crowding with an overlapping of the features of target and flankers within the same
298 receptive field or an inappropriate feature integration.²⁹ For other authors, it is the
299 representation that is degraded with a combination of the target's features and those of the
300 flankers modifying the appearance of the target.³⁰⁻³¹ These accounts are not mutually
301 exclusive as crowding is not a unitary process. Impaired processing in V1 can propagate to
302 later stages of visual processing in higher cortical areas, such as V4, where receptive fields are
303 larger and may integrate the features of target and flankers. Neuroimaging studies have been
304 carried out in normally sighted individuals to investigate the neural origin of crowding with a
305 measure of BOLD signals resulting from crowded and non-crowded peripheral stimuli in
306 various cortical areas. Millin et al.³² found that crowding was associated with suppressed
307 fMRI signals as early as V1. Anderson et al.³³ found that crowding influences neural
308 responses throughout the visual cortex and increases in strength from V1 to V4, suggesting a
309 multistage process. Although there is growing evidence from MRI studies in humans that
310 glaucomatous damage propagates from the optic nerve to the cortex, resulting in structural
311 and functional cortical changes,³⁴⁻³⁵ we cannot speculate on a cortical origin of the higher
312 susceptibility to central crowding in glaucoma in the present psychophysical study. The
313 significant crowding effects were not found to be related to the central visual field defect in
314 all patients. Patient 15, with a mild central field defect, exhibited a better performance for the
315 isolated T than for the target with flankers, while Patient 4, with a severe central field defect,
316 performed better in the crowded than in the uncrowded condition, suggesting inter-individual
317 variability in susceptibility to crowding. Inter-observer variability on central crowding has
318 been reported previously in another ocular pathology: strabismic amblyopia.³⁶⁻³⁷

319

320 **Limitations:** In contrast to the literature no crowding effect was observed in normally sighted
321 controls. The experimental conditions: an exposure duration long enough to trigger a saccade
322 and a large edge-to-edge spacing might be responsible for the lack of crowding effect and a
323 performance at ceiling in this group. Nevertheless, a crowding effect was observed both in
324 foveal and lateral presentations in patients with the same experimental conditions.

325

326 **Conclusion**

327 The present study demonstrates that susceptibility to foveal crowding reported in a
328 previous study with faces as stimuli¹³ extends to letters. A higher effect of crowding was also
329 observed in parafoveal vision in patients, but the crowding distance was modulated by
330 contrast. Susceptibility to crowding was related to central visual field defect but not to
331 contrast sensitivity in central vision, probably because the stimuli were displayed above
332 contrast threshold. A higher effect of crowding was not observed in all patients. The patients
333 were not questioned about their reading frequency and general interest in the practice. In
334 normally sighted observers, Chung³⁸ showed that crowding in peripheral vision could be
335 reduced through training.

336

337 **References**

- 338
- 339 1. Smith ND, Glen FC, Mönster VM, et al. Using Eye Tracking to Assess Reading
340 Performance in Patients with Glaucoma: A Within-Person Study. *J of Ophthalmol.* 2014; 1-
341 10. <http://dx.doi.org/10.1155/2014/120528>.
- 342
- 343 2. Boltezar L, Cvenkel B. Reading performance in glaucoma. *Acta Ophthalmol.* 2015; e321-
344 e322. doi: 10.1111/aos.12613.
- 345
- 346 3. Kwon M, Liu R, Patel BN, et al. Slow reading in glaucoma: is it due to the shrinking visual
347 span in central vision? *Invest Ophthalmol Vis Sci.* 2017; 58: 5810–5818.
- 348
- 349 4. Smith ND, Crabb DP, Glen FC, et al. Eye Movements in Patients with Glaucoma When
350 Viewing Images of Everyday Scenes. *Seeing and Perceiving.* 2012; 25: 471–492.
- 351
- 352 5. Garric C, Rouland JF, Lenoble Q. Glaucoma and Computer Use: Do Contrast and Color
353 Enhancements Improve Visual Comfort in Patients? *Ophthalmol Glaucoma,* 2021; 4(5):531-
354 540. doi: 10.1016/j.ogla.2021.01.006.
- 355
- 356 6. Glen FC, Crabb DP, Smith ND et al. Do patients with glaucoma have difficulty recognizing
357 faces? *Invest Ophthalmol Vis Sci.* 2012; 53: 3629-3637.
- 358
- 359 7. Roux-Sibilon, Rutgé, F, Aptel, F, et al. Scene and human face recognition in the central
360 vision of patients with glaucoma. *PLoS One.* 2018; 13: e0193465. doi.org/10.1371/journal.pone.0193465
- 361
- 362 8. Schafer A, Rouland JF, Peyrin C, et al. Glaucoma affects viewing distance for recognition
363 of sex and facial expression. *Invest Ophthalmol Vis Sci.* 2018; 59 : 4921-4928. doi:
364 10.1167/iovs.18-24875.
- 365
- 366 9. Lahav K, Levkovitch-Verbin H, Belkin M, et al. Reduced Mesopic and Photopic Foveal
367 Contrast Sensitivity in Glaucoma. *Arch Ophthalmol.* 2011; 129: 16-22.
- 368
- 369 10. Lek JJ, Vingrys AJ, McKendrick AM. Rapid contrast adaptation in glaucoma and in
370 aging. *Invest Ophthalmol Vis Sci.* 2014; 55: 3171–3178.

- 371 11. Ansari EA, Morgan JE, Snowden RJ. Psychophysical characterisation of early functional
372 loss in glaucoma and ocular hypertension. *Br J Ophthalmol.* 2002; 86: 1131–1135.
373
- 374 12. Ikeda MC, Hamada KU, Bando AH, et al. Interventions to Improve Reading
375 Performance in Glaucoma. *Ophthalmology Glaucoma.* 2021; 4: 624-631
376
- 377 13. Stievenard A, Rouland JF, Peyrin C, et al. Sensitivity to central crowding for faces in
378 patients with glaucoma. *J Glaucoma.* 2021; 30: 140-147.
- 379 14. Pelli DG, Tillman KA . The uncrowded window of object recognition. *Nat Neurosci.*
380 2008;11: 1129–1135.
381
- 382 15. Pelli, D. G., Palomares, M. & Majaj, N. J. Crowding is unlike ordinary masking:
383 distinguishing feature integration from detection. *J of vis.* 2004; 4, 1136-1169.
384
385
- 386 16. Shamsi F, Liu R, Kwon M. Binocularly asymmetric crowding in glaucoma and a lack of
387 binocular summation in crowding. *Invest Ophthalmol Vis Sci.* 2022; 63:36.
388 <https://doi.org/10.1167/iovs.63.1.36>
389
- 390 17. Bouma H. Interaction effects in parafoveal letter recognition. *Nature.*1970; 226: 177-178.
391
- 392 18. Chung STL, Levi DM, Legge GE. Spatial-frequency and contrast properties of crowding.
393 *Vis Res.* 2001; 41: 1833–1850.
- 394 19. Rashal E, Yeshurun Y. Contrast dissimilarity effects on crowding are not simply another
395 case of target saliency. *J of Vis.* 2014; 14:9. doi: 10.1167/14.6.9.
396
- 397 20. Herzog MH, Sayim B, Manassi M, et al. What crowds in crowding? *J of Vis.*2016; 16: 25.
398 doi: 10.1167/16.11.25.
- 399 21. Coates DR, Chin JM, Chung STL. Factors Affecting Crowded Acuity: Eccentricity and
400 Contrast. *Optom Vis Sci.* 2013; 90 : 1-21 . doi:10.1097/OPX.0b013e31829908a4.
401
- 402 22. Legge GE, Ahn SJ, Klitz TS, et al. Psychophysics of Reading-XVI . The Visual Span in
403 Normal and Low Vision. *Vis Res.* 1997; 37: 1999-2010.

- 404 23. Legge GE, Rubin GS, Luebker A. Psychophysics of reading. V. The role of contrast in
405 normal vision. *Vis Res.* 1987, 27: 1165–1177.
406
- 407 24. Chung STL, Tjan BS. Spatial-frequency and contrast properties of reading in central and
408 peripheral vision. *J Vis.* 2009; 9: 1-19. doi: 10.1167/9.9.16.
- 409 25. Ogata NG, Boer ER, Daga FB, et al. Visual crowding in glaucoma. *Invest Ophthalmol Vis*
410 *Sci.* 2019; 60: 538–543. <https://doi.org/10.1167/iovs.18-25150>.
411
- 412 26. Pelli DG. Crowding: A cortical constraint on object recognition. *Curr Opin*
413 *Neurobiol.* 2008; 18 : 445–451.
414
- 415 27. Herzog MH, Manassi M. Uncorking the bottleneck of crowding: a fresh look at object
416 recognition. *Curr Opin Behav Sci.* 2015; 1: 86–93.
417 <https://doi.org/10.1016/j.cobeha.2014.10.006>
418
- 419 28. Doerig A, Bornet A, Rosenholtz R, et al. Beyond Bouma’s window: How to explain
420 global aspects of crowding? *PLoS Comput Biol.* 2019; 15: e1006580.
421 <https://doi.org/10.1371/journal.pcbi.1006580>
422
- 423 29. Nandy AS, Tjan BS. Saccade-confounded image statistics explain visual crowding. *Nat*
424 *Neurosci.* 2012; 15: 463–469.
- 425 30. Sayim B, Wagemans J. Appearance changes and error characteristics in crowding
426 revealed by drawings. *J of Vis.* 2017; 17 :8, 1–16.
- 427 31. Melnik N, Coates DR, Sayim B. Emergent features in the crowding zone: When target-
428 flanker grouping surmounts crowding. *J of Vis.* 2018; 18:19. doi: 10.1167/18.9.19.
429
- 430 32. Millin R, Arman AC, Chung STL et al. Visual Crowding in V1. *Cerebral Cortex.* 2014;
431 24: 3107–3115.
432
- 433 33. Anderson EJ, Dakin SC, Schwarzkopf DM, et al. The Neural Correlates of Crowding-
434 Induced Changes in Appearance. *Current Biology.* 2012; 22, 1199–1206.
435

- 436 34. Gupta N, Yucel YH. What Changes Can We Expect in the Brain of Glaucoma Patients?
437 *Surv Ophthalmol.* 2007; 52 Suppl 2:S122-6. doi: 10.1016/j.survophthal.2007.08.006.
438
- 439 35. Lawlor M, Danesh-Meyer H, Levin LA, et al. (2018). Glaucoma and the brain: Trans-
440 synaptic degeneration, structural change, and implications for neuroprotection. *Surv*
441 *Ophthalmol.* 2018; 63: 296-306. doi: 10.1016/j.survophthal.2017.09.010.
- 442 36. Norgett Y, Siderov J. Effect of stimulus configuration on crowding in strabismic
443 Amblyopia. *J Vis.* 2017 ; 17 : 1–14.
444
- 445 37. Bonneh, S, Sagi, D, Polat U. Local and non-local deficits in amblyopia: Acuity and
446 spatial interactions. *Vis Res.* 2004; 44 : 3099–3110.
447
- 448 38. Chung STL (2007). Learning to identify crowded letters: does it improve reading speed? .
449 *Vis Res.* 2007; 47: 3150-3159
450

451

Figure and table captions

452 **Table1:** Clinical and demographic data for patients and controls. Acuity is expressed in
453 LogMar. CS = contrast sensitivity, R = Right eye L = Left eye.

454

455 **Fig.1.** 10-2 visual field of the tested eye of the 17 patients. RE = right eye, LE = left eye.

456

457 **Fig.2.** Schematic illustration of the experimental paradigm for foveal and parafoveal
458 presentations.

459

460 **Fig.3.** Z-scores as a function of spacing conditions and levels of contrast in foveal
461 presentations for patients with glaucoma G and healthy controls H. ** : $p < .002$.

462 **Fig.4.** Individual data in terms of Z-scores as a function of the visual field defect (MD) in
463 foveal presentations for the isolated T and the crowded condition without spacing (THT).

464 **Fig.5.** Z-scores as a function of spacing conditions and levels of contrast for patients with
465 glaucoma G and healthy controls H in the parafoveal visual field. * : $p < .05$.

466

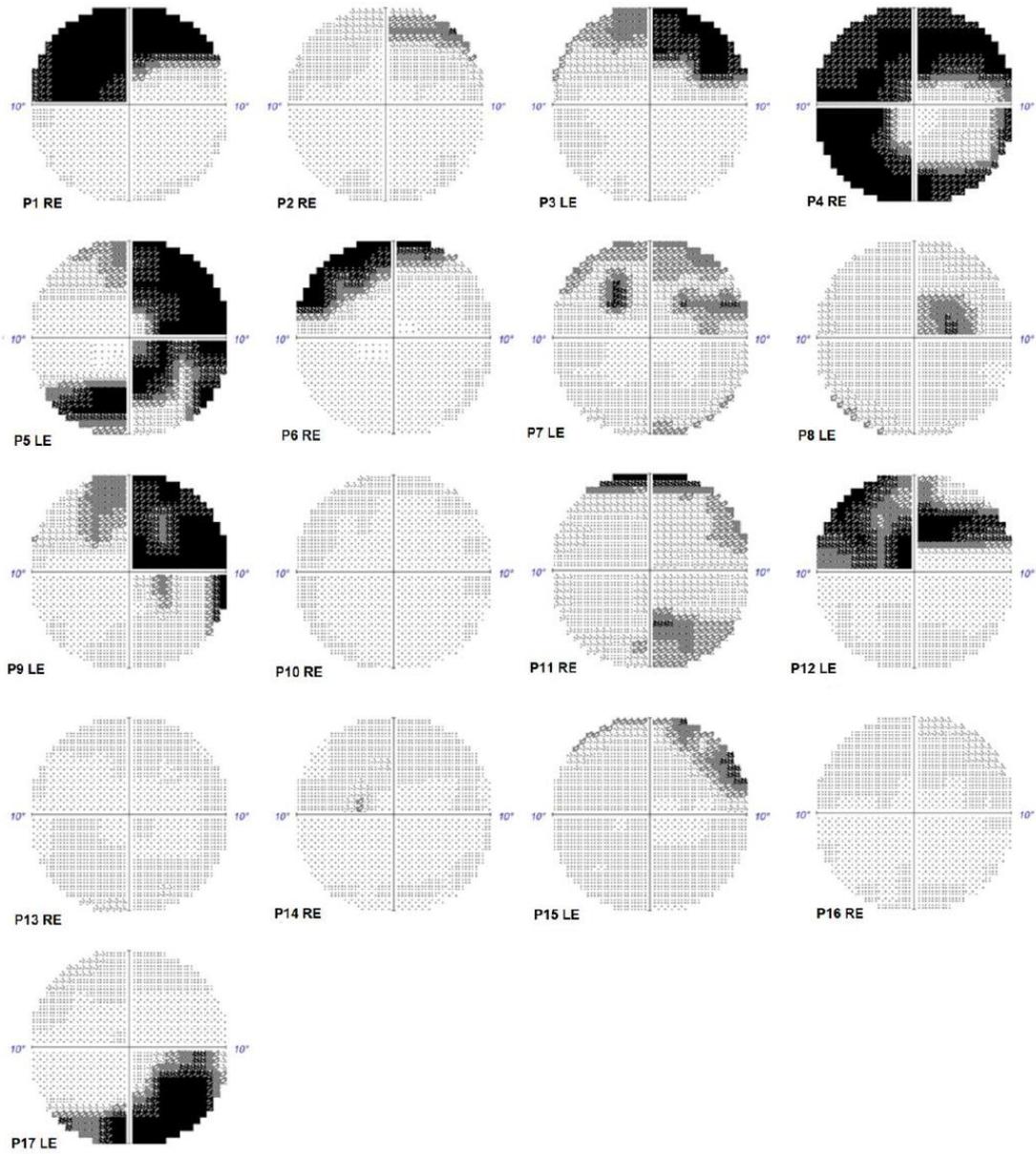
467 **Table1:** Clinical and demographic data for patients and controls. Acuity is expressed in
 468 LogMar. CS = contrast sensitivity, R = Right eye L = Left eye.

Patients	LogCS	MD	Acuity	Age	Tested eye	Gender
1	1.9	-12,19	0.0	60	RE	F
2	1.39	-2,75	0.0	69	RE	M
3	1.73	-7,1	0.1	73	LE	F
4	1.2	-24,26	0.1	74	RE	M
5	2.06	-18,53	0.0	54	LE	F
6	1.58	-4,04	0.0	69	RE	M
7	1.74	-7,27	0.1	63	LE	F
8	1.56	-5,46	0.1	71	LE	M
9	1.32	-11,38	0.0	71	LE	F
10	1.5	-1,17	0.0	60	RE	M
11	1.24	-8,88	0.1	70	RE	F
12	1.9	-11,34	0.0	47	LE	F
13	1.72	-3,24	0.0	49	RE	F
14	1.43	-1,55	0.0	74	RE	F
15	1.67	-4,85	0.1	71	LE	F
16	1.96	-2,15	0.0	66	RE	M
17	1.9	-9,03	0.0	73	LE	F
Controls	LogCS		Acuity	Age	Tested eye	Gender
1	1.76		0.1	78	RE	M
2	1.83		0.0	64	RE	F
3	1.98		0.0	58	RE	F
4	1.93		0.0	61	LE	F
5	1.94		0.0	60	RE	F
6	1.9		0.0	53	LE	M
7	1.86		0.0	65	RE	F
8	1.99		0.0	60	LE	M
9	1.86		0.0	59	LE	M
10	1.94		0.0	53	RE	M
11	2.14		0.0	60	RE	F
12	1.92		0.0	58	LE	F
13	1.78		0.0	77	RE	M
14	1.93		0.0	62	RE	F
15	1.88		0.0	61	RE	F

469

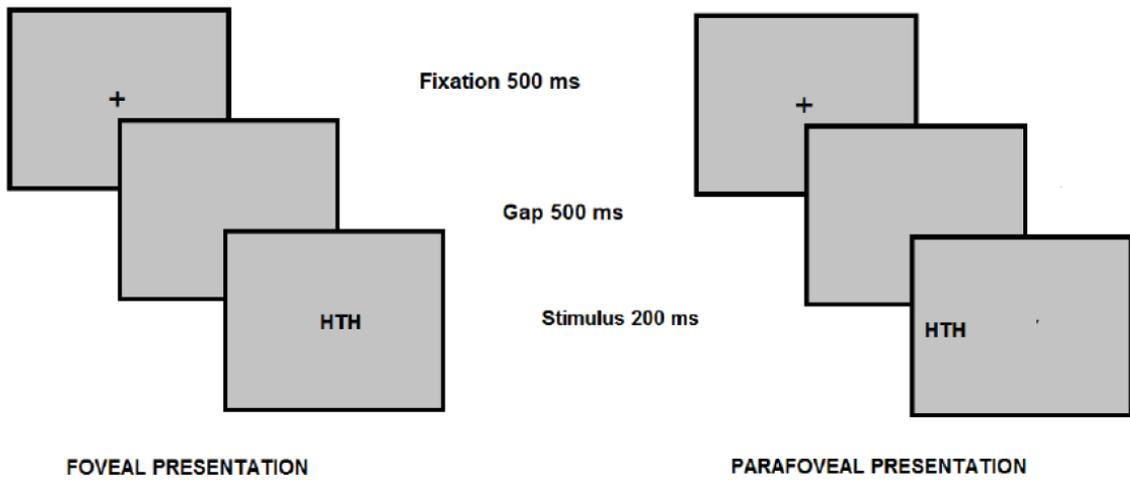
470

Fig.1.



474

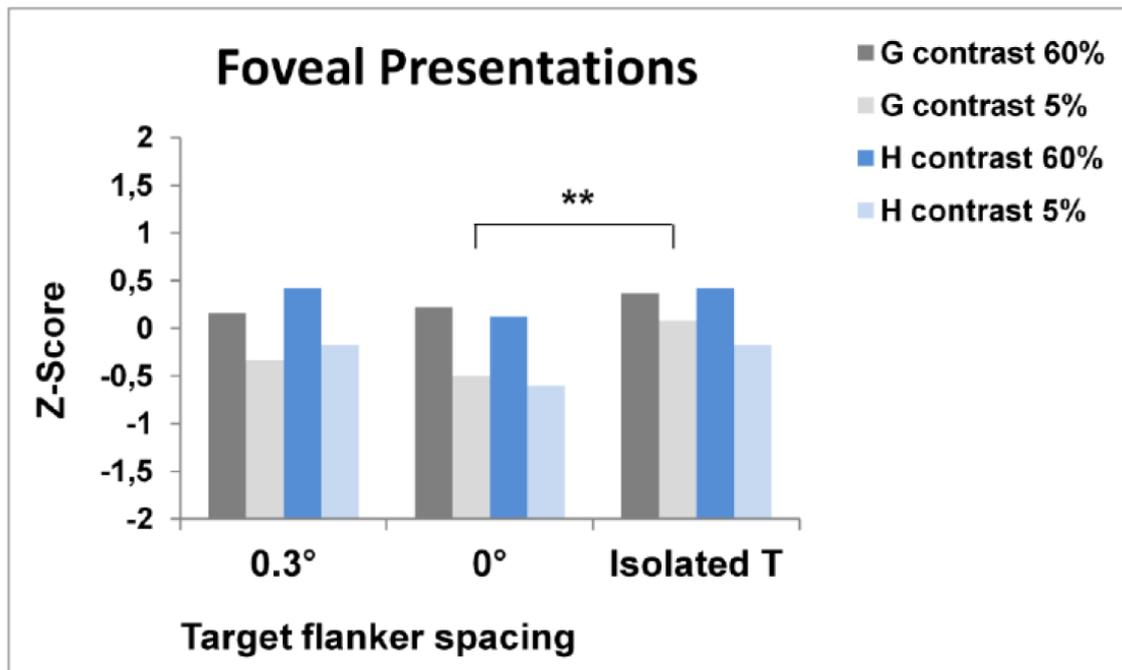
Fig.2.



475

476

Fig.3.

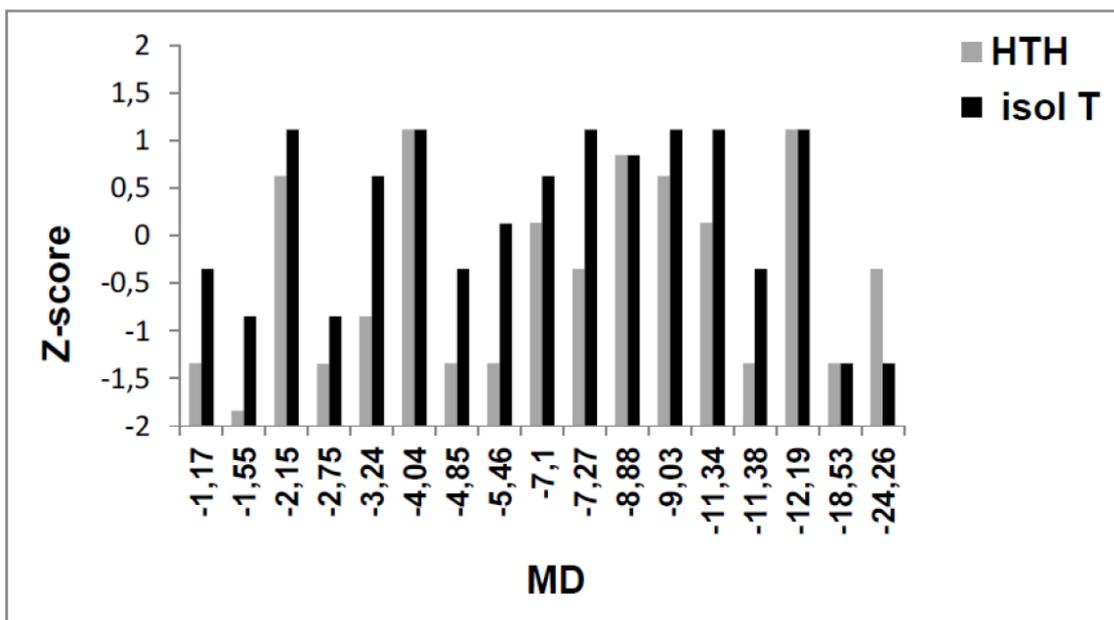


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479

480

Fig.4.



481

482

Fig.5.

