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4

5 **Spatial frequency bands used by patients with glaucoma to recognize facial**
6 **expressions**

7 **Running head: Face recognition in glaucoma**

8

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19

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27

28

SYNOPSIS

29 We investigated the contribution of spatial frequencies as mechanisms for impaired face
30 perception in glaucoma. Patients exhibit a deficit in both low and high frequencies potentially
31 leading to misinterpretation of some facial expressions.

32

ABSTRACT

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The authors investigated the influence of spatial frequencies in foveal vision in glaucomatous patients in a recognition task of facial expressions. Nineteen patients, 16 age-matched and 14 young controls saw centrally presented photographs of faces. Participants categorized the facial expressions as happy, angry or neutral. Two versions were tested: filtered faces of either low (LSF) or high (HSF) spatial frequency content and hybrid faces constructed from a face with LSF content superimposed on a face with HSF content with differing facial expressions. Compared to age-matched controls a significant deficit was observed both on HSF and on LSF filtered faces for patients. Controls, but not patients, were biased towards the HSF component of the hybrid faces. Different spatial frequencies are normally used to recognize different facial expressions. Impaired processing of a spatial frequency bandwidth due to an ocular pathology can therefore lead to misinterpretation of emotions, and impact on social interactions.

48 Glaucoma is an ocular disease involving the progressive destruction of the optic nerve.
49 Traditionally, glaucoma has been considered to affect peripheral vision first, with central
50 vision relatively preserved until later stages of the disease. However, more recently it has
51 been recognized that central vision including the macular area can be affected at all stages of
52 the disease (Hood et al., 2014; Hood 2017). Central visual impairments in glaucoma involve
53 low level processes such as form, contrast (McKendrick et al 2002), in addition to defects in
54 motion perception (Shabana et al., 2003) and saccadic eye movements (Lamirel et al 2014).
55 There is also evidence of abnormal foveal perception in several studies involving more
56 complex stimuli. Lenoble et al (2016) found reduced accuracy, and longer response times,
57 compared to age-matched controls in a categorization task of grey level photographs of
58 objects (2.5°) presented foveally with a contrast of 50%. With random strings of three letters
59 presented centrally for 200 ms with a contrast of 99%, Kwon et al. (2017) found lower
60 accuracy in the identification of foveally displayed letters in glaucomatous patients than in
61 normally sighted age-matched participants.

62 Though face perception has not been the subject of much interest in glaucoma,
63 laboratory based studies (Glen et al., 2012; 2013; Mazzoli et al., 2019) converge to show an
64 abnormal processing of centrally displayed faces in patients with glaucoma as compared to
65 age-matched normally sighted controls. For instance, people with glaucoma need closer faces
66 to recognize the facial expression, the identity and even the gender of the person approaching
67 (Schafer et al., 2017). Yet, the mechanisms underlying the deficit in face perception and its
68 impact on social cognition are not yet elucidated.

69 Psychophysical (Graham 1980; De Valois & de Valois 1990) and physiological
70 (Campbell & Robson, 1968) studies have shown that the visual system analyzes the visual
71 input with independent filters, each tuned to specific spatial frequency channels. It has been
72 demonstrated in many studies on young normally sighted observers that some spatial scales
73 are preferentially selected over others depending on task requirements (Brady & Oliva 2012;
74 Schyns & Oliva 1994; 1997). For instance, with faces, categorization of gender can be
75 performed based on LSF components (Goffaux et al., 2003). Low frequencies are sufficient to
76 recognize some facial expressions (happiness, surprise, and disgust) whilst other expressions
77 (anger, fear, sadness) require higher frequencies (Smith & Schyns 2009) or mid frequencies
78 for pain (Charbonneau et al 2021). With faces as stimuli, impaired processing of a spatial
79 frequency bandwidth can therefore lead to misinterpretation of emotions, and impact on social
80 interactions.

81 The availability of the relevant spatial frequency information for a given task can also
82 be modulated by the contrast sensitivity of the observer. In order to better understand the
83 mechanisms underlying the deficit in face perception, and specifically in the recognition of
84 some facial expressions in glaucoma, we investigated the hypothesis of a difficulty to
85 perceive relevant spatial frequency bands as a possible account.

86 A technique that has been used to investigate the relevant spatial frequency bands for a
87 given task is filtering images with low pass and high pass filters, in addition to using hybrid
88 images (Schyns & Oliva, 1994; 1997; Prete et al., 2015; Tommasi et al., 2021). Hybrid
89 stimuli mix two different pictures at two different spatial frequency bandwidths. For instance,
90 they combine a low spatial frequency content face image of a man or a woman with a
91 particular expression (e.g., happy) with a high spatial frequency content face image of the
92 opposite gender with a different expression (e.g., angry). Hybrid images are not realistic
93 stimuli but, because they are composed of two images, each at a different spatial frequency
94 range, the image reported by the participant directly informs about the spatial scale perceived.
95 In normally sighted observers the use of hybrid faces has shown that the visual system can
96 preferentially select spatial frequency scales depending on the relevant information required
97 to perform a task. For instance categorization on gender was LSF-biased whilst categorization
98 as expressive/non expressive was HFS biased (Schyns & Oliva 1999).

99 In this exploratory study, we displayed high pass, low pass and hybrid faces in foveal
100 vision to patients with glaucoma and age matched normally sighted controls, and also to
101 young participants to assess the effect of normal aging. We used the same stimuli, the same
102 filtering, and the same presentation conditions as Laprevote et al. (2010) who found that
103 healthy young observers were biased towards the HSF component of the hybrid face in a
104 categorization task on facial expression. We tested the hypothesis that recognition of facial
105 expression, a function that is best accomplished in central vision, would be impaired in
106 participants with glaucoma.

107 With young participants we expected a bias towards HSF in foveal vision both for
108 filtered and for hybrid images as in Laprevote et al (2010) study. It has been shown that
109 contrast sensitivity declines with normal aging (Owsley 2011) and that reduced contrast
110 sensitivity is more detrimental to high than to low spatial frequencies (Ramanoel et al., 2015).
111 We therefore expected that the bias towards HSF observed in young participants would be
112 reduced in older normally sighted participants. It is now recognized that glaucoma impacts
113 central visual function even at early stages of the disease (Hood et al 2014). As foveal vision
114 is involved in the processing of featural information conveyed by HSF we expected that

115 glaucoma would affect the perception of HSF filtered images more than LSF images and that
116 patients would rely more on the LSF component of the hybrid faces compared to controls.

117

118 **METHOD**

119

120 Participants

121

122 The characteristics of the population are summarized in Table 1 for patients and in Table 2 for
123 controls.

124 Nineteen participants (8 males), with clinically significant visual field defects in both eyes
125 due to Primary Open Angle Glaucoma, were recruited from the department of ophthalmology
126 in Lille University Hospital. They ranged in age from 36 to 84 years (mean 67.4, SD: 10.1).
127 Each patient underwent a complete ophthalmological examination including a visual field
128 evaluation, a measure of acuity, of contrast sensitivity using the Pelli-Robson chart, and
129 optical coherence tomography (OCT; Cirrus OCT HD-OCT 4000 Carl Zeiss Meditec, Inc.
130 Dublin CA 94568 USA) just before the experiment. Their mean monocular visual acuity was
131 at least equal to 0.1 LogMar. Visual field sensitivity was measured with a Humphrey Field
132 Analyzer (HFA, Carl Zeiss Meditec, Dublin CA, USA). As we tested in central vision, the 10-
133 2 stimulus pattern (SITA standard) was employed. The 10-2 field analyzer measures 68
134 spotlights in the central 10 degrees of the visual field. Table 1 provides the clinical data for
135 each eye. The visual field of only one eye could be measured on 9/19 patients. The other eye
136 was at an advanced stage and was not measurable due to loss of fixation and/or too many false
137 negatives or false positives (see Table1). Sixteen age-matched controls (8 males) ranging in
138 age from 37 to 81 years (mean: 64.5 SD: 9.4) were recruited within the relatives of patients
139 and within the staff of the department of ophthalmology. None of them had a family history of
140 glaucoma and none had signs of glaucoma, cataract or macular degeneration. An evaluation of
141 their visual acuity was performed just before the testing. Patients and age-matched controls
142 did not differ significantly in age ($F(1, 33) = 0.81, p = 0.37$).

143 All the patients and controls older than 60 years were assessed with the French version of the
144 Mini Mental State Examination (MMSE) to check for age related cognitive impairment. A
145 MMSE score lower than 27/30 was a criterion of exclusion. A group of 14 young participants
146 (8 males) was included to dissociate the effect of aging from the effect of pathology. They
147 were medical students ranging in age from 21 to 32 (mean 26 years SD: 4.2). An evaluation of

148 their visual acuity was performed just before the testing. The minimum acuity required for
149 selection was 0.1 LogMar.

150 During the test all participants, patients, young and older controls wore optical corrections
151 adapted to a distance of 140 cm.

152 The study was approved by the ethics committee in behavioral sciences of the university of
153 Lille (RVPG 2018 – 270-60). In accordance with the tenets of the Declaration of Helsinki
154 written informed consent was obtained from all participants.

155

156

157 **[tables 1 and 2 about here]**

158

159 **Stimuli**

160

161 The stimuli were the set of high and low filtered faces and hybrid faces provided by
162 Aude Oliva (MIT Boston) and used in Laprevote et al. ⁽²⁰¹⁰⁾ In that set, faces from different
163 individuals are aligned so that inner and outer face characteristics overlap (see Figure 1).
164 Images were 256×256 pixels size, in grayscale. Faces from 12 different individuals were used
165 (six males and six females), each showing three different expressions: angry, happy or
166 neutral. There was a low-pass version (below 8 cycles/face) and a high-pass version (above 24
167 cycles/face) of each face (see examples in Figure 1), for a total of 36 LSF-only faces and 36
168 HSF-only faces. The description of the filters used can be found in Oliva and Schyns (1997).
169 The 36 LSF and the 36 HSF filtered faces were used to create 96 hybrid faces. These hybrid
170 faces were built by overlapping the low-pass filtered face from one individual with the high-
171 pass filtered face of another individual. Each hybrid was composed of one male face and one
172 female face. One face of the hybrid displayed a neutral expression and the other face
173 displayed either a happy or an angry expression. Peyrin et al (2017) found that contrast
174 enhancement of HSF filtered scenes improved performance in the residual parafoveal vision
175 of patients with macular degeneration. We chose not to enhance the contrast of the HSF
176 filtered faces as keeping contrast the same for both spatial scales is presumably more relevant
177 to daily tasks.

178

179

180 **Procedure**

181

182 Participants were seated 140 cm from a large screen (84 inches Company Speechi, Lille,
183 France). At that viewing distance the stimuli subtended $2.5^\circ \times 2.5^\circ$ of visual angle. Within the
184 black square of $2.5^\circ \times 2.5^\circ$ the angular size of the face was $2.32^\circ \times 1.92^\circ$. There was no chin
185 rest and viewing was binocular. Stimuli were presented in a dimly illuminated room with the
186 light off and a weak light coming from the edges of venetian blind of the window. A central
187 white fixation cross was shown for 1 sec on a black background. It was followed, 100 ms
188 later, by a face stimulus displayed centrally for 150 ms. Participants were tested on two
189 blocks of trials in the experimental session. The Filtered block contained 72 trials including
190 36 HSF filtered images and 36 LSF filtered images, each filtered version was composed of 12
191 (6 males) neutral, 12 (6 males) angry and 12 (6 males) happy faces. The Hybrid block
192 contained 96 images composed of an expressive face (happy, angry) and a neutral face. The
193 neutral face appeared 48 times in LSF (superimposed to 24 HSF happy and to 24 HSF angry
194 faces) and 48 times in HSF (superimposed to 24 LSF happy and to 24 LSF angry faces). The
195 faces were the same in the filtered and in the hybrid versions as hybrids were built from the
196 filtered faces. The order of the filtered and hybrid blocks was counterbalanced between
197 participants in each group. Within each block (filtered/hybrid) the different faces, spatial
198 frequencies and expressions were randomly presented. The task was a 3 alternative forced
199 choice on facial expression (happy, angry, neutral) for both versions of images (filtered and
200 hybrid). The three facial expressions, and the 3 versions (low pass, high pass and hybrid),
201 were presented on paper before the experiment in order to ensure that observers understood
202 the task. Participants responded orally: Happy, Angry or Neutral. The verbal answer was
203 coded (H, A, N) by the experimenter on the keyboard of the computer.

204 A training session, including 3 blocks of 20 trials with randomly presented LSF and
205 HSF filtered faces was performed for patients and age-matched controls. This training session
206 was performed to familiarize the older participants with a short exposure time. We started
207 with a block of 20 trials presented for 300 ms, followed by 20 new trials presented for 250 ms
208 and 20 new trials presented for 200 ms. Performance was not recorded in the training session
209 but the experimenter provided a feed back on each response. No feed back was given in the
210 experimental session.

211

212 **Statistical analysis**

213 A Post hoc power analysis was conducted with the software G_Power (Faul et al 2007). It
214 showed that the power of our design was: Power (1- β err prob) = .98 (α = .05; effect size =
215 1.9). Statistical analyzes were conducted with the software Systat 8 (Systat Software, Inc San
216 Jose, California). Two repeated measure ANOVAs were conducted, one for filtered images
217 and one for hybrid images. For filtered faces the dependent variable was the percentage of
218 correct responses for each spatial frequency. For hybrid faces the dependent variable was the
219 percentage of spatial frequency bandwidth used by the participant to recognize the facial
220 expression within the two expressions that composed the hybrid face. The within factors were
221 the spatial frequency (HSF vs LSF) and the facial expression (angry, happy, neutral). The
222 group (young, older controls, patients with glaucoma) was the between factor. We used
223 Cohen's d to determine the effect sizes when standard deviations were similar between groups
224 with identical sample sizes. When the groups have different sample sizes, Hedges' g makes it
225 possible to weight the effect size according to the relative size of each sample. A bonferoni
226 correction was applied when a T test was used. The results are presented in Figure 2 for
227 filtered and hybrid faces. Figure 3 illustrates performance for each facial expression.
228 Individual data are presented in Figure 4 for patients in relation with clinical data.. The
229 Spearman R was used to check any relationship between a bias towards a spatial frequency
230 bandwidth and the visual field defect, age, contrast sensitivity and acuity.

231

232

[Figure 1 about here]

233

234 **RESULTS**

235

236 **Patients and age-matched controls: effect of pathology**

237

238 **Filtered faces**

239

240
241 Accuracy was better for controls than for patients (83.5% vs 52.7% $F(1, 33) = 32.7, p < .001$
242 Hedge's $g = 1.84$). On average accuracy was better for LSF than for HSF filtered images
243 (71.3% vs 64.8% $F(1, 33) = 12.8, p < .01$ Cohen's $d = 0.27$) in the two groups (see Figure 2).
244 The interaction between group and spatial frequency was not significant ($F(1, 33) = 3.3, p =$
245 0.79). A separate analysis for the two spatial scales showed that performance was
246 significantly lower for patients than for controls both on HSF (by 34.1% $F(1, 34) = 21.7,$

247 $p < .001$ Hedge's $g = 1.80$) and on LSF (by 27.5% $F(1, 34) = 34.9$, $p < .001$ Hedge's $g = 1.99$).
248 The patients' performance was significantly above chance (33%) both for HSF ($t(18) = 2.76$,
249 $p < .01$) and for LSF ($t(18) = 5.9$, $p < .001$). There was a significant effect of facial expression
250 ($F(2, 66) = 3.36$, $p < .05$). Figure 3 shows that age-matched controls were more accurate to
251 categorize expressive than neutral faces: happy: 89.3%, angry: 85.8%, neutral: 75.3%,
252 (angry/neutral $F(1, 15) = 11.4$, $p < .004$; happy/neutral $F(1, 15) = 19.7$, $p < .001$, happy/angry
253 $F(1, 15) = 0.19$, $p = 0.67$). Patients were more impaired at recognizing an angry (42.3%) than
254 a happy (55.6%) or a neutral expression (60.1%) (angry/neutral $F(1, 18) = 8.8$, $p < .01$;
255 happy/angry $F(1, 18) = 7.6$, $p < .01$, happy/neutral $F(1, 18) = 1.4$, $p = 0.24$). The interaction
256 between group and facial expression was significant ($F(2, 66) = 9.7$, $p < .001$). For patients the
257 decrease in accuracy for HSF was greater for expressive than for neutral faces.

258 Within the patient's group 15/19 patients (Figure 4) exhibited a better accuracy for
259 LSF than for HSF (by 13.7%). For these patients the mean MD of their best eye was -10.9 and
260 the mean contrast sensitivity of the best eye was 1.52. The remaining 4/19 patients (P2, P3, P4
261 and P12 see Figure 4) exhibited a better performance for HSF than for LSF filtered images.
262 The mean MD of their best eye was -10.7 and their mean contrast sensitivity was 1.72. The
263 loss in ganglion cells (measured as the GCIPL thickness) was larger in the subgroup of
264 patients who exhibited a better accuracy for LSF than for those who exhibited a better
265 accuracy for HSF (57 vs 65 μm). The differences between the subgroups of patients were not
266 statistically significant for MD ($t(17) = 0.07$, $p = 0.942$), contrast sensitivity ($t(17) = 1.87$,
267 $p < .08$) and GCIPL ($t(14) = 1.23$, $p = 0.23$).

268 A significant correlation was found between contrast sensitivity and age ($r = -.507$,
269 $p < .027$) and between contrast sensitivity and acuity ($r = -.737$, $p < .001$). No significant
270 correlation was found between the MD of the best eye and the other variables. Contrast
271 sensitivity was related with both LSF ($r = -.710$, $p < .001$) and HSF ($r = -.733$, $p < .001$).

272

273

Figure 2 about here]

274

275

276 **Hybrid faces**

277

278 As hybrid stimuli are composed of faces in two SF bandwidths the facial expression reported
279 indicated which spatial scale was preferentially perceived. The spatial frequency bandwidth
280 selected for response is presented in Figure 2.

281 The percentage of errors (ex: responding angry for a neutral/happy hybrid) was significantly
282 higher for patients than for controls (8.22% vs 20.6% $F(1, 33) = 9.7, p < .01$ Hedge's $g = 1.07$).
283 The Anova was conducted on correct responses. There was no significant main effect of
284 spatial frequency ($F(1, 33) = 1.95, p = 0.17$) but spatial frequency interacted significantly with
285 group ($F(1, 33) = 4.95, p < .05$). Controls selected more the HSF component of the hybrid face
286 than patients (55.6% vs 38.2% $F(1,33) = 9, p < .01$ Hedge's $g = 1.09$). There was no difference
287 between groups for the LSF component of the hybrid face (controls: 38% vs patients: 42.2%
288 $F(1,33) = 0.56, p = 0.45$). The analysis also showed a significant main effect of facial
289 expression ($F(2, 66) = 10.8, p < .001$) with a better performance for happy (53.9%) than for
290 angry (36.5%) and for neutral faces (40.1%). This result was observed for both groups. The
291 interaction between group and facial expression was not significant ($F(2, 66) = 0.8, p = 0.44$).
292 Fig. 3 shows a bias towards HSF for the three facial expressions in the control group. Patients
293 exhibited a slight bias towards LSF for happy faces and equivalent performance in the two SF
294 bands for angry and neutral faces.

295 Within the patient's group 12/19 patients selected more (by 13%) the LSF than the
296 HSF component of the hybrid image. For these patients the mean MD of their best eye was -
297 9.7 and the mean contrast sensitivity was 1.51. The remaining 7/19 patients responded on the
298 basis of the HSF (by 11.4%) than on the LSF component of the hybrid image. The mean MD
299 of their best eye was -12.9 and their mean contrast sensitivity was 1.63. The loss in ganglion
300 cells (measured as the GCIPL thickness) was larger in the subgroup of patients who exhibited
301 a bias towards the LSF component of the hybrid face than for those who exhibited a bias
302 towards the HSF component (55 vs 65 μm). The differences between the subgroups were not
303 statistically significant in terms of MD ($t(17) = 1.25, p = 0.30$), contrast sensitivity ($t(17) =$
304 $1.05, p = 0.227$) and GCIPL ($t(14) = 1.98, p < .067$).

305
306 No significant correlations were found between a bias toward the LSF component of the
307 hybrid image and age ($r = -.387, p = .101$), the MD of the best eye ($r = -.250, p = .300$),
308 acuity ($r = .019, p = .937$) and contrast sensitivity ($r = .239, p = .324$).

309
310 **[Figure 3 about here]**

311
312 To summarize: Compared to age-matched controls, glaucoma affected the perception of both
313 high and low spatial frequencies when a single face was displayed, in the filtered version.
314 When two faces were superimposed, in the hybrid version, normally sighted participants saw

315 more easily the HSF component of the face. The perception of HSF was more impaired in
316 patients than in controls in the hybrid version. In both versions of images, filtered and hybrid,
317 the patients who exhibited a deficit in the perception of HSF were those with lower contrast
318 sensitivity in central vision and the greater loss in ganglion cells. However, due to the small
319 samples the differences were not statistically significant.

320

321 **[Figure 4 about here]**

322

323 **Young and older controls: effect of aging**

324

325 **Non hybrid filtered faces**

326

327 Young and older participants differed significantly on accuracy (young: 88.7% vs older:
328 83.5% $F(1, 28) = 4.1, p < .05$ Hedge's $g = 0.61$). There was no main effect of spatial frequency
329 ($F(1, 28) = 0.3, p = 0.56$). Spatial frequency did not interact significantly with group ($F(1, 29)$
330 $= 1.7, p = 0.20$). The difference between groups just failed to reach statistical significance for
331 HSF ($F(1, 28) = 3.7, p < .06$) and performance was equivalent for LSF ($F(1, 28) = 2, p = 0.16$).
332 The effect of facial expression was significant ($F(2, 56) = 21.3, p < .001$) with a better
333 performance for expressive faces (happy: 91.6%, angry: 89.3%) than for neutral faces
334 (77.2%) in both groups. The only correlation observed for age-matched controls was between
335 age and acuity ($r = .614, p < .01$). The oldest participants exhibited a lower acuity.

336

337 **Hybrid faces**

338

339 The percentage of errors on the facial expression was significantly higher for older than for
340 young participants (8.22% vs 4.5% $F(1, 28) = 6.4, p < .01$ Hedge's $g = 0.86$). The Anova was
341 carried out on correct responses. There was a significant main effect of spatial frequency ($F(1,$
342 $28) = 30.6, p < .001$ Cohen's $d = 1.79$) and a significant interaction between group and spatial
343 frequency ($F(1, 28) = 7.7, p < .01$) resulting from a strong bias towards HSF for young
344 participants (HSF: 73.9% vs LSF: 20.8% ($F(1, 13) = 44.5, p < .001$ Cohen's $d = 3.65$) and a
345 smaller bias towards HSF in older participants (55.6% vs 38% ($F(1, 15) = 3.3, p < .08$
346 Cohen's $d = 0.94$). There was also a significant main effect of facial expression ($F(2, 56) =$
347 $18.1, p < .001$) with a better performance for happy faces (56.9%) than for angry (40%) and for
348 neutral faces (44.3%) in both groups.

349

350 To summarize: Aging affected more the perception of HSF than LSF and this was amplified
351 by the superimposition of a low pass face in the hybrid version.

352

353

DISCUSSION

354

355 In natural environments our visual system is exposed to a large range of spatial
356 frequencies. To reliably categorize stimuli participants must attend to the information that is
357 more appropriate (i.e., diagnostic) for the task. The diagnostic band of spatial frequencies for
358 a given task depends on category specific diagnostic information in object frequencies (e.g.,
359 global versus featural information). For instance, reliably identifying a person requires both
360 medium (5–8 cycles per face), and high (8–12 cycles per face) spatial frequency information
361 (Fiorentini et al., 1983).

362

363 Consistent with Laprevote et al. (2010) we observed an equivalent performance for
364 LSF and HSF filtered faces and a bias towards the HSF component of the hybrid faces in
365 normally sighted young participants. Compared to young participants, older controls were
366 impaired with HSF images, particularly in the hybrid version. Behavioral experiments
367 investigating the use of spatial frequencies in normal elderly people have produced conflicting
368 results. For instance, using sine-wave gratings, Govenlock et al. (2010) found that spatial
369 frequency selectivity was not affected by normal aging. Ramanoel et al. (2015) used more
370 complex stimuli. Young and older normally sighted participants had to categorize grey level
371 photographs of scenes filtered in LSF (SF cutoff 0.5, 1, and 2 cpd) and in HSF (SF cutoff 3, 6,
372 and 12 cpd) as indoor/outdoor. They reported a deficit in performance for older participants
373 only when categorizing HSF filtered scenes. The same tendency was observed in the present
374 study with filtered faces. In the hybrid version, the smaller bias towards the HSF component
375 in older participants, as compared to younger ones, suggests that older participants were more
376 sensitive to interference from the LSF component on the HSF component of the hybrid face.
377 With hybrid faces as stimuli Prete et al (2015) found that the emotional LSF component of
378 the hybrid face can be subliminally processed, with a 28 ms presentation time, and affect the
379 perception of the HSF component.

379

380 Compared to age-matched controls the deficit in HSF was not confined to hybrid faces
381 for patients. The perception of both low and high frequencies was affected in filtered faces.
382 However, in both filtered and hybrid versions a majority of patients exhibited a better
383 performance for LSF images. Though the differences were not statistically significant due to

383 the small samples, the subgroup of patients who exhibited a better accuracy for LSF in the
384 filtered version had a lower contrast sensitivity and a greater loss in retinal ganglion cells than
385 the subgroup who exhibited a better accuracy for HSF. These results suggest that the
386 impairment does not result from a mere sensitivity to masking or to overlapping hybrid faces
387 appearing scrambled. The deficit can be attributed to reduced contrast sensitivity and ganglion
388 cell loss in central vision in glaucoma. A deficit in contrast sensitivity has been reported in
389 foveal vision in patients with glaucoma despite good visual acuity (Lahav et al., 2011;
390 Wilensky et al., 2001) and also in patients diagnosed with glaucoma in the absence of visual
391 field defects on standard perimetry (Ichhpujani et al., 2020). Glen et al. (2012) found that
392 patients with significant central 10-2 defects in the best eye performed worse in the
393 Cambridge face memory test than patients without significant central vision loss and age-
394 matched controls. Contrast sensitivity was an important factor for explaining face-recognition
395 performance in their study. In the present experiment the performance of young and older
396 controls indicates that categorization of facial expression relies more on HSFs. If HSFs are
397 not, or are less, visible to patients they have to base their decision on LSFs which were less
398 efficient than HSFs to recognize the facial expressions at the angular size used in our
399 experiment.

400 In the present study both young and older controls were more likely to select the HSF
401 than the LSF component of the hybrid face for response. This result contrasts with Schyns and
402 Oliva (1999) who found, with the same stimuli and the same low and high-pass cut-offs, that
403 normally sighted young participants exhibited a bias towards the LSF component of the
404 hybrid face to categorize facial expressions as happy, angry or neutral. Conflicting results
405 have been reported in the literature regarding categorization of facial expressions in normally
406 sighted young observers. Studies have reported different use of spatial frequencies depending
407 on the facial expression (Kumar & Srinivasan 2011), on the number of facial expressions to
408 discriminate (Jennings et al., 2017), on the spatial frequency cut-offs (Charbonneau et al.,
409 2021), and on whether high and low frequency filtered faces are equated in contrast and
410 luminance (Vlamings et al., 2009). The bias towards HSFs in our study is likely due to the
411 longer exposure time (150 ms) than in Schyns and Oliva (1999) who used a presentation time
412 of 50 ms with the same task and the same stimuli. Indeed, Wang et al. (2017) reported a LSF
413 preference for the expressions of pain, happiness and fear with hybrid faces but this low
414 frequency preference decreased with the increase in presentation duration (33, 67, 150, and
415 300 ms).

416 The patients were more impaired at categorizing angry than happy faces. This is
417 consistent with the literature supporting a dominant role of LSFs in the processing of the
418 facial expression of happiness. Compared to other expressions like anger, sadness and fear for
419 instance, happiness has been found to be recognizable from a far distance (Smith & Schyns
420 2009) or in peripheral vision (for Calvo et al 2014; Goren & Wilson 2006, Smith and Rossit
421 2018) where the visual system must rely on the lower spatial frequency content of the
422 stimulus due to the decrease in receptors. As patients performed better with the LSFs the
423 expression of happiness was less affected than angry and neutral expressions.

424

425 **Limitations:** There are several limitations for this study. The presentation duration
426 (150 ms) does not reflect natural conditions of face perception which is usually unlimited in
427 time. However, if patients require more time than normally sighted people to identify faces
428 and facial expressions then they might be impaired when watching movies or when scanning
429 several faces in a room. The angular size used (2.5°) was designed to assess foveal perception
430 in glaucoma but it is smaller than the angular size of a face at conversational distance. To
431 reduce the duration of the test for older participants, patients and controls, we used only three
432 facial expressions and arbitrary spatial frequency cutoffs. Yet, several studies have shown that
433 the relevant band of spatial frequency varies as a function of the facial expression. For
434 instance, Charbonneau et al (2021) demonstrated that the visibility of features relevant to
435 categorize the expression of pain (brow furrowing, the wrinkling of the nose with the raising
436 of the upper lip, and the narrowing of the eyes) can be altered by filtering. In manipulating
437 distance they showed that categorizing pain among other facial expressions is more accurate
438 when stimuli are displayed in a distance range of 1.2–4.8 m from the observer rendering
439 available a broad range of object based SFs from low to high with a crucial role of mid
440 frequencies (between 16 and 32 cycles per face). In a future study we plan to use more basic
441 facial expressions and an angular size corresponding to a human face at more natural viewing
442 distances.

443

444

445 **Conclusion:** Previous studies have demonstrated that people with glaucoma exhibit
446 difficulties in key central visual functions, such as reading (Burton et al., 2014; Smith et al.;
447 2014; Kwon et al., 2017) and face recognition (Glen et al., 2012; 2013; Schafer et al., 2017;
448 Stievenard et al., 2021). Our study supports these previous findings, but further demonstrates
449 that people with glaucoma are impaired in the categorization of facial expression in foveal

450 vision and that this impairment results in part from a deficit in the perception of both high and
451 low spatial frequencies. Notably, despite all our patients having manifest visual field loss on
452 clinical perimetry, most had a relatively normal visual field in the very central test area and
453 normal visual acuity, yet still demonstrated difficulty with the facial expression task.

454 **Implications:** Facial expressions reflect a person's emotion and intentions. Rapidly decoding
455 accurate information from the expressions is thus an important skill for successful social
456 behavior. Poor face perception resulting from visual deficits is known to have a profound
457 impact on a person's ability to participate efficiently in social interactions and to the quality of
458 life (Jin et al., 2019).

459

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FIGURE AND TABLE LEGEND

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Table 1: clinical and demographic data about patients. MD = Mean Deviation (10-2) in decibel. VA= visual acuity (LogMar), L = left eye, R = right eye, VF = visual field, CS = contrast sensitivity, RNFL = retinal nerve fiber layer (μm). GCIPL = ganglion cell-inner plexiform layer (μm), - = not measured.

Table 2: Age and acuity (VA) of young and older controls.

Figure 1: Examples of HSF and LSF filtered faces exhibiting the three facial expressions selected in the study and a hybrid face that combines a low-pass filtered man with a happy expression and a high-pass filtered woman face with a neutral expression. View the images from a distance, or defocus, to reveal the low-pass component of the hybrid image. (Stimuli provided by Aude Oliva).

Figure 2: Top: percentage of spatial frequency bandwidth selected by each participant in each group for hybrid faces. The vertical bars represent the means and confidence intervals . Bottom: percentage of correct responses, means and confidence intervals, for low frequency and high frequency filtered faces as a function of the group of participants.

Figure 3. Mean accuracy (and standard errors) for each group as a function of the facial expression and the version of faces (filtered/hybrid).

Figure 4: Bias towards a SF bandwidth (computed as HSF – LSF) for hybrid and filtered images and for each patients as a function of the MD and contrast sensitivity (CS) of the best eye.

609 **Table1**

Patients N°	Age	VA L	VA R	MD L	MD R	GCIL L	GCIL R	RNFL L	RNFL R	CS L	CS R
1	66	0	0	-17.0	-6.9	59	63	62	57	1.65	1.8
2	36	0	0	-6.2	-7.7	54	59	42	47	1.8	1.8
3	63	0.1	0	-16.3	-6.3	52	58	57	71	1.65	1.8
4	65	-	0.1	-	-19.5	88	-	91	68	-	1.65
5	76	0	-	-9.9	-	-	-	-	-	-	1.65
6	76	0.1	0.1	-19.2	-20.5	46	45	67	57	1.05	1.2
7	58	0.1	0.1	-3.9	-3.6	90	58	84	70	1.35	1.35
8	71	0.1	0.1	-2.9	-3.1	64	64	57	56	1.35	1.2
9	72	0	-	-9.8	-	59	67	60	64	1.65	-
10	84	0.1	-	-11.3	-	56	72	50	80	1.35	-
11	64	0	0	-15.2	-25.0	-	-	-	-	1.65	1.65
12	63	-	0	-	-10.9	76	83	83	71	-	1.65
13	78	0	0.1	-4.8	-7.2	64	46	69	69	1.35	1.35
14	68	0	0	-18.0	-10.3	59	64	64	58	1.8	1.8
15	68	0	-	-7.3	-	55	65	55	76	1.65	-
16	59	-	0	-	-17.7	-	47	-	46	-	1.65
17	74	-	0	-	-13.5	75	44	66	55	-	1.65
18	74	0.1	-	-21.1	-	56	-	67	-	1.35	-
19	67	-	0.1	-	-10.9	-	71	-	61	-	1.5

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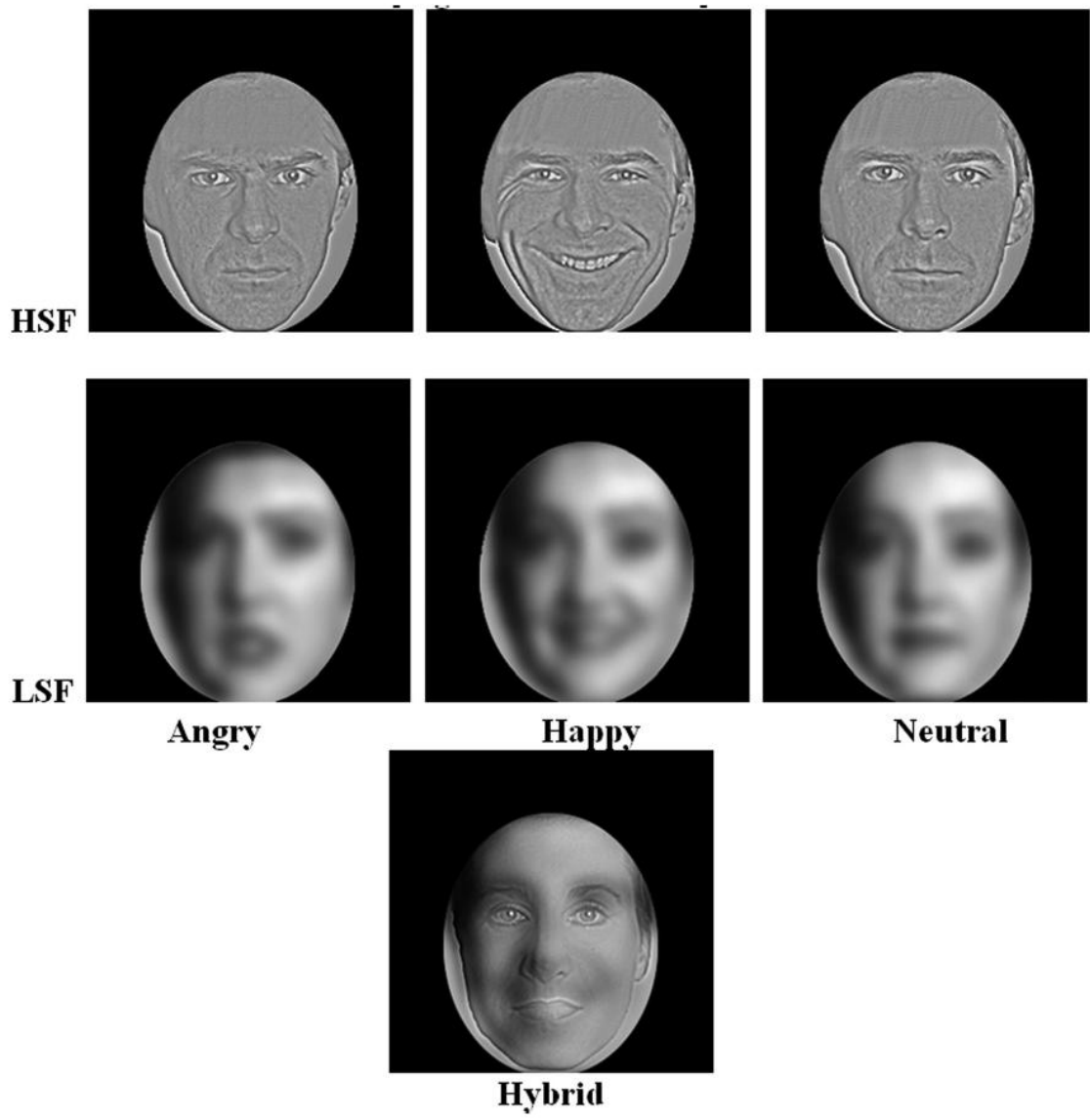
Table 2

Young Participants				Age-matched controls			
Participant N°	Age	VA L	VA R	Patients N°	Age	VA L	VA R
1	30	0	0	1	74	0	0
2	28	0	0	2	62	0	0
3	25	0	0	3	64	0	0
4	31	0	0	4	71	0	0
5	30	0	0	5	57	0	0
6	29	0	0	6	59	0	0
7	25	0	0	7	56	0	0
8	20	0	0	8	75	0.1	0.1
9	20	0	0	9	84	0.1	0.1
10	21	0	0	10	68	0	0
11	25	0	0	11	73	0	0
12	32	0	0	12	45	0	0
13	27	0	0	13	60	0	0
14	21	0	0	14	66	0	0
				15	62	0	0
				16	55	0	0

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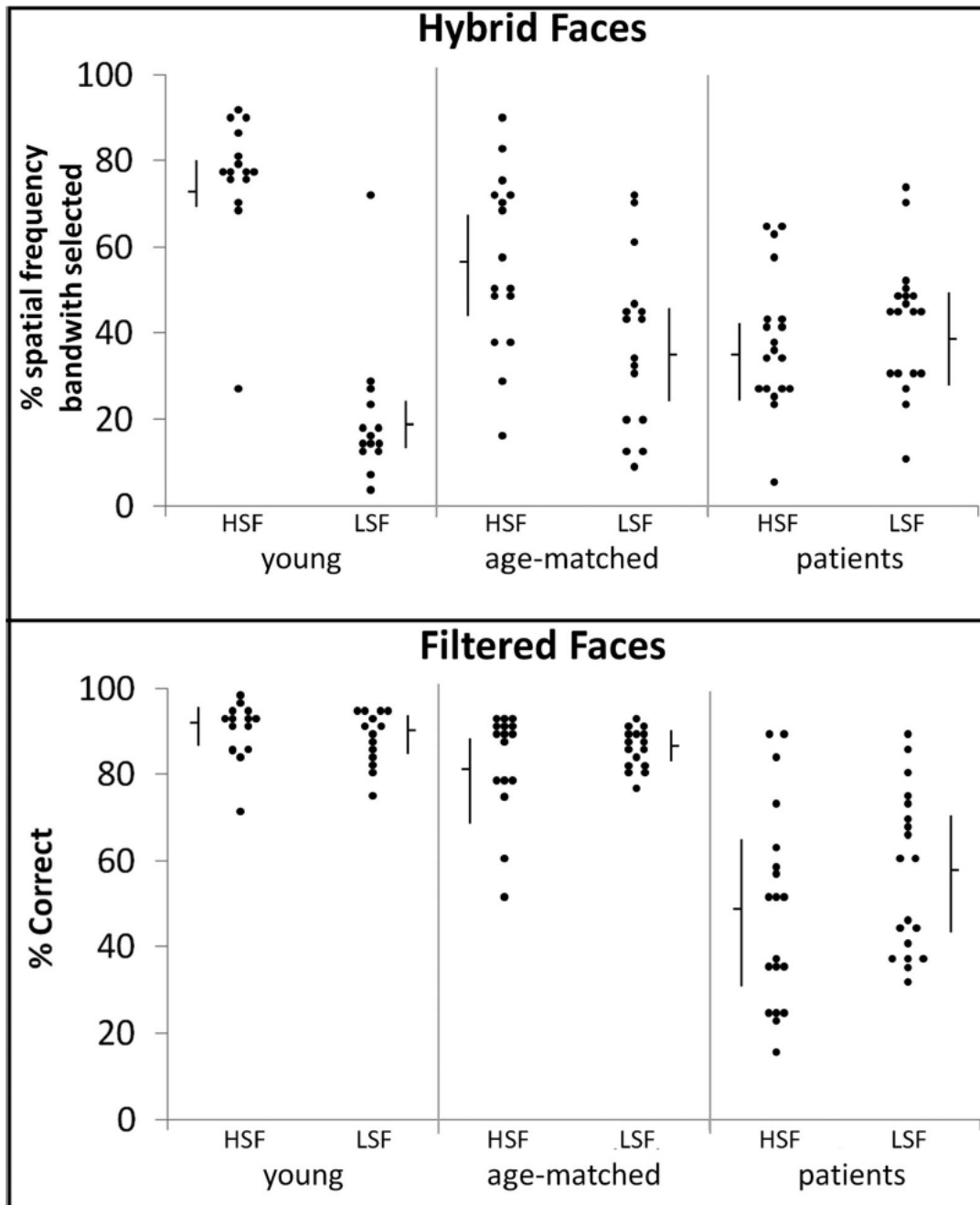
614 Fig.1.



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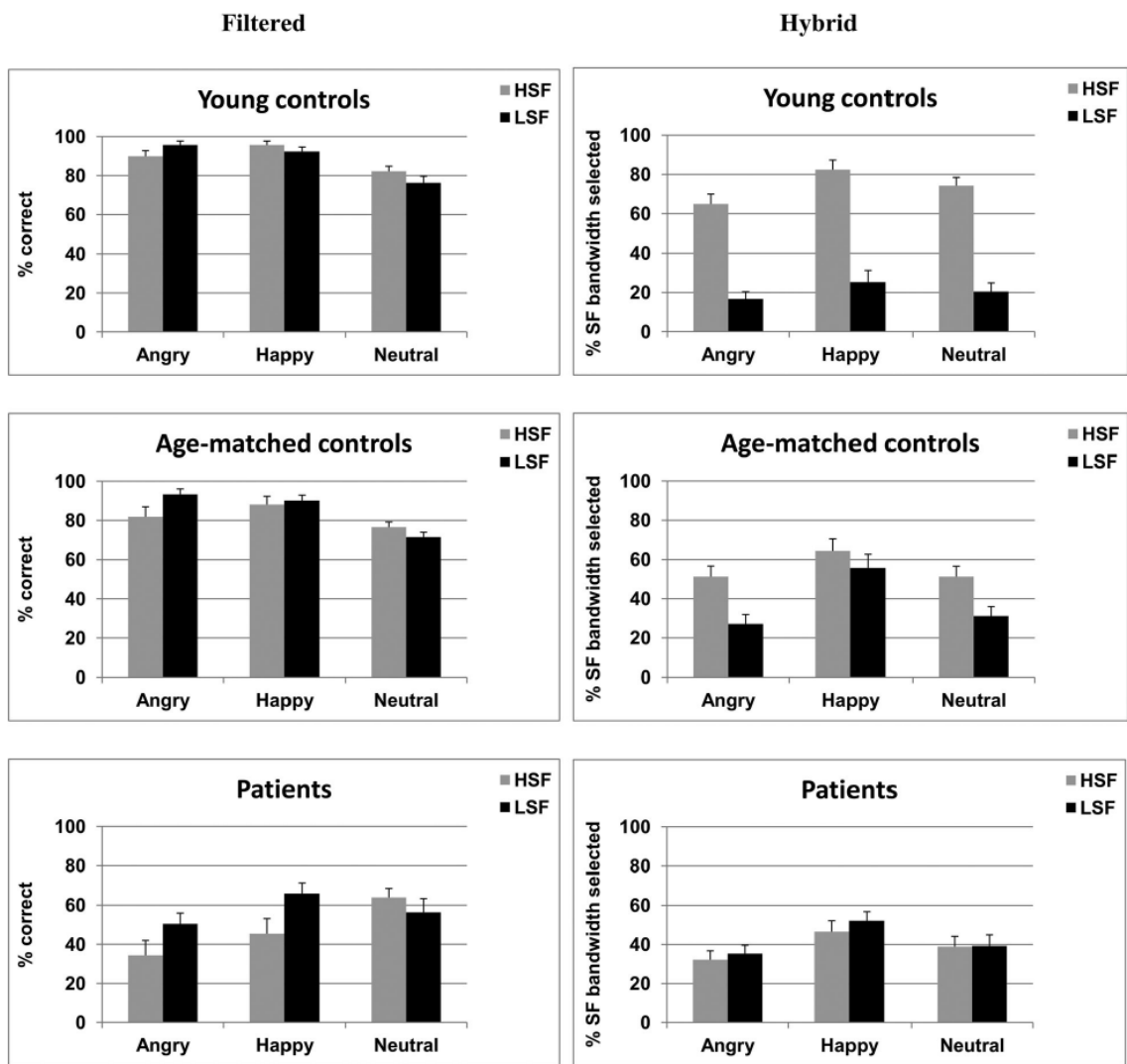
617 Fig.2



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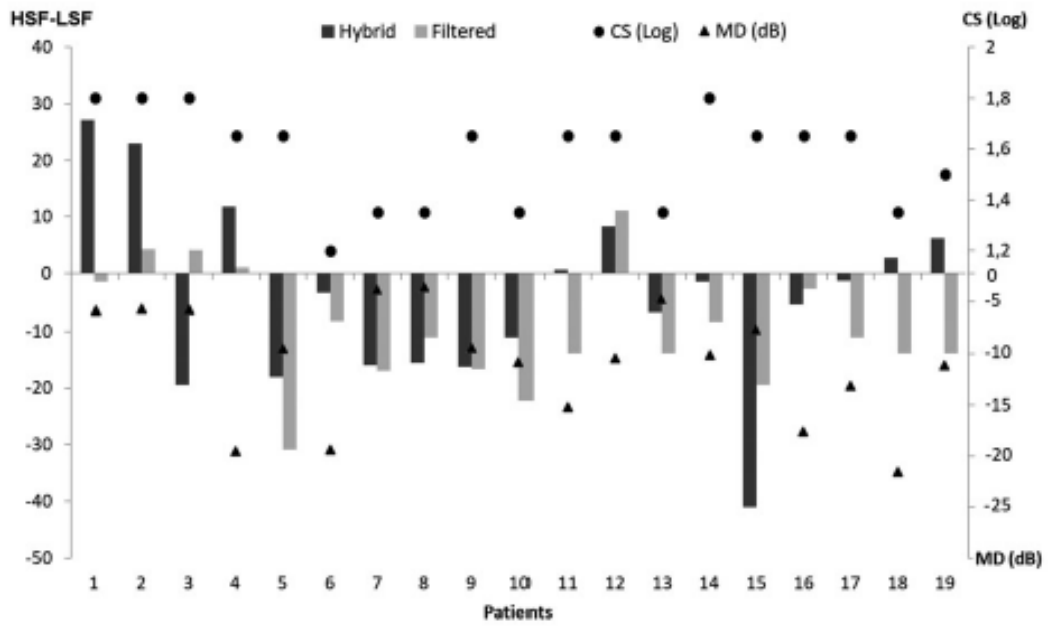
620 Fig.3.



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623 Fig.4.



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