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1 **Atypical visual field asymmetries in redundancy masking**

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16

17 **Keywords**

18 Redundancy masking, visual field asymmetries, peripheral vision, crowding, regularity perception, spatial
19 compression

20

21 **Author Contributions**

22 B.S., D.R.C., and F.Z.Y. designed the study and prepared the manuscript. F.Z.Y. collected and analyzed
23 the data and prepared the figures. All authors interpreted the data and reviewed the manuscript.

24

25 **Competing interests**

26 The authors declare no competing interests.

27

28 **Abstract**

29 Redundancy masking is the reduction of the perceived number of items in repeating patterns. It shares a
30 number of characteristics with crowding, the impairment of target identification in visual clutter. Crowding
31 strongly depends on the location of the target in the visual field. For example, it is stronger in the upper
32 compared to the lower visual field, and usually weakest on the horizontal meridian. This pattern of visual
33 field asymmetries is common in spatial vision, as revealed by tasks measuring, e.g., spatial resolution and
34 contrast sensitivity. Here, to characterize redundancy masking and reveal its similarities and differences to

35 other spatial tasks, we investigated whether redundancy masking shows the same typical visual field
36 asymmetries. Observers were presented with three to six radially arranged lines at 10° eccentricity at one
37 of eight locations around fixation and were asked to report the number of lines. We found asymmetries that
38 differed pronouncedly from those found in crowding. Redundancy masking did not differ between upper
39 and lower visual fields. Importantly, redundancy masking was stronger on the horizontal meridian than on
40 the vertical meridian, the opposite of what is usually found in crowding. These results show that redundancy
41 masking diverges from crowding in regard to visual field asymmetries, suggesting different underlying
42 mechanisms of redundancy masking and crowding. We suggest that the observed atypical visual field
43 asymmetries in redundancy masking are due to the superior extraction of regularity and a more pronounced
44 compression of visual space on the horizontal compared to the vertical meridian.

45

46 **Keywords**

47 Redundancy masking, visual field asymmetries, peripheral vision, crowding, regularity perception, spatial
48 compression

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50

51 **Introduction**

52 In redundancy masking (RM), the perceived number of identical items is reduced (Sayim & Taylor,
53 2019; Taylor & Sayim, 2018; 2020; Yildirim, Coates, & Sayim, 2020, 2021). For example, when presented
54 with three identical, nearby letters in the visual periphery, observers frequently reported only two letters (in
55 a free naming and drawing task; Sayim & Taylor, 2019; Figure 1a). Recently, several characteristics of RM
56 have been revealed (Yildirim et al., 2020, 2021). RM shows a pronounced radial-tangential anisotropy:
57 when items were arranged radially relative to fixation, there was strong RM; when they were arranged
58 tangentially, there was no RM (Yildirim et al., 2020). RM has also been shown to depend on the spacing
59 between items: Larger spacing between items decreased RM compared to smaller spacings (Yildirim et al.,
60 2020). Also, size affected the strength of RM: Increasing the width of items decreased RM (Yildirim et al.,
61 2020). Importantly, the strength of RM strongly depended on the spatial regularity of the stimulus. Varying
62 the regularity of peripherally presented line arrays by vertically or horizontally jittering the positions of the
63 lines, it was found that there was strong RM with items that were arranged regularly and no RM with items
64 that were arranged irregularly (Yildirim et al., 2020). A similar dependence on regularity was observed when
65 observers indicated the number of tilted lines, with strong RM when all (three) lines were tilted in the same
66 direction and no RM when one of the lines was tilted in the opposite direction (Rummens & Sayim, in
67 revision).

68 RM seems to be one way the visual system copes with large amounts of information: redundant
69 information in regular, repeating patterns is discarded and does not enter conscious awareness (see also
70 Brady, Konkle, & Alvarez, 2009). However, the underlying mechanisms of RM are still unknown. A recent
71 finding suggests that RM is linked to compressions of visual space (Yildirim, Coates, & Sayim, 2019).

72 Observers were asked to indicate the number of lines, and judge the spacing between the outermost lines
73 (i.e., the overall horizontal extent of the entire line array) or - in a different experiment - the spacing between
74 adjacent lines (alternative choices from varying spacings) (Yildirim, Coates, & Sayim, 2019). We found that
75 in trials in which RM occurred (in particular when 3 lines were presented and 2 reported), but not in trials in
76 which no RM occurred (3 lines presented, 3 reported), observers reported a smaller overall extent and a
77 larger spacing between adjacent lines compared to the correct extent. Investigating the perceived centroid
78 of the line arrays, we found further evidence for a compression of space, and the loss of the central (of
79 three) lines in RM: Observers accurately reported the location of a probe relative to the centroid of the line
80 array in both RM and no RM trials (if the perceived location of the probe deviated from the correct centroid
81 of the line array in RM trials, it would suggest that an outer line, rather than a central line (especially when
82 three lines were presented), was lost due to RM). These results suggest that RM goes hand in hand with
83 compressions of peripheral visual space (Yildirim et al., 2019). Irrespective of the compression of visual
84 space, RM could be due to insufficient attentional resolution in peripheral vision similar to what was
85 proposed for crowding, the impairment of object recognition in clutter (Figure 1a) (Chakravarthi &
86 Cavanagh, 2007; He, Cavanagh, & Intriligator, 1996, 1997; Intriligator & Cavanagh, 2001). In attentionally
87 demanding tasks, such as crowded target discrimination, superior performance was found in the lower
88 compared to the upper visual field. This asymmetry was attributed to higher attentional resolution in the
89 lower than the upper visual field (He et al., 1996). Limits of attentional resolution might well underlie RM. If
90 that was the case one would expect a similar upper/lower visual field asymmetry as in crowding.

91 RM is related to crowding (Bouma, 1970, 1973; Herzog, Sayim, Chicherov, & Manassi, 2015; Levi,
92 2008; Melnik, Coates, & Sayim, 2018, 2020; Pelli, Palomares, & Majaj, 2004; Rummens & Sayim, 2019;
93 2021; Sayim & Cavanagh, 2013; Sayim, Greenwood, & Cavanagh, 2014; Strasburger, Harvey, &
94 Rentschler, 1991; Strasburger, 2020; Whitney & Levi, 2011). A loss of information possibly related to RM,
95 such as the omissions or truncations of elements (Sayim & Wagemans, 2017) was shown in a number of
96 recent crowding studies (Coates, Wagemans, & Sayim, 2017; Coates, Bernard, & Chung, 2019; Sayim &
97 Wagemans, 2017; see also Korte, 1923). For example, using a gaze-contingent peripheral presentation
98 and appearance capture (drawing) paradigm, frequent omissions and truncations of elements in letter and
99 letter-like targets indicated target diminishment in crowding (Sayim & Wagemans, 2017). Similar results –
100 possibly due to 'self-crowding' (Martelli, Majaj, & Pelli, 2005; Zhang, Zhang, Liu, & Yu, 2009) - were found
101 with complex, peripherally presented letters and letter-like shapes in isolation (Melnik, Coates, & Sayim,
102 2021). The investigation of errors in peripherally presented lower-case letter trigrams revealed a similar
103 pattern of diminishment in crowding: Letter features appearing in both a flanking letter and the target letter
104 (such as an ascender or descender) were often omitted in the reported target (Coates et al., 2019).
105 Common characteristics of RM and crowding include radial-tangential anisotropies (Greenwood, Szinte,
106 Sayim, & Cavanagh, 2017; Petrov & Meleshkevich, 2011a; Toet & Levi, 1992; Yildirim et al., 2020), a
107 reduction of interference with increasing spacing between items (Bouma, 1970; Levi, Hariharan, & Klein,
108 2002; Pelli et al., 2004; Strasburger et al., 1991; Yildirim et al., 2020), and a dependence on spatial

109 regularity (Manassi, Sayim, & Herzog, 2012; Saarela, Westheimer, & Herzog, 2010; Sayim, Westheimer, &
110 Herzog, 2011; Yildirim et al., 2020). In addition to the radial-tangential anisotropy, crowding has been shown
111 to be subject to a number of other asymmetries. For example, flankers on the outer (peripheral) side of the
112 target yield more crowding than flankers on the inner (central) side, the ‘inner-outer asymmetry’ of crowding
113 (Banks, Bachrach, & Larson, 1977; Petrov & Meleshkevich, 2011a, 2011b; Shechter & Yashar, 2021).
114 Importantly, the strength of crowding is asymmetric across isoeccentric locations in the visual field.
115 Specifically, at a fixed eccentricity, crowding is stronger in the upper compared to the lower visual field (i.e.,
116 vertical meridian asymmetry: VMA) (Fortenbaugh, Silver, & Robertson, 2015; Greenwood et al., 2017; He
117 et al., 1996; Intriligator & Cavanagh, 2001), and usually weaker on the horizontal meridian compared to the
118 vertical meridian (i.e., horizontal-vertical asymmetry: HVA) (Greenwood et al., 2017; Nazir, 1992). This
119 pattern of visual field asymmetries (Figure 1b) is common in vision, and has been found for spatial resolution
120 (Altpeter, Mackeben, & Trauzettel-Klosinski, 2000; Barbot, Xue, & Carrasco, 2021; Greenwood et al., 2017;
121 Nazir, 1992), contrast sensitivity (Abrams, Nizam, & Carrasco, 2012; Cameron, Tai, & Carrasco, 2002;
122 Carrasco, Talgar, & Cameron, 2001), motion (Fuller & Carrasco, 2009; Lakha & Humphreys, 2005), hue
123 (Levine & McAnany, 2005), saccadic precision and spatial localization (Greenwood et al., 2017), saccadic
124 latency (Greene, Brown, & Dauphin, 2014; Greenwood et al., 2017; Petrova & Wentura, 2012) and texture
125 segmentation (Talgar & Carrasco, 2002). Not all tasks, however, show all of the typical anisotropies. For
126 example, performance in a three-dot bisection task was better in the lower than upper visual field, but not
127 different between horizontal and vertical meridians (Greenwood et al., 2017). Performance in vernier acuity
128 for horizontally and vertically aligned target lines seemed not to differ between horizontal and vertical
129 meridians (Westheimer, 2005). Here, we investigated whether RM shows the same typical visual field
130 asymmetries as several related phenomena.

131 We presented three to six radially arranged lines at one of the eight locations at 10° eccentricity
132 around fixation (in cardinal and inter-cardinal directions), and asked observers to report the number of lines.
133 We found asymmetries that differ pronouncedly from those found in most spatial tasks. RM did not differ
134 between the upper and lower visual fields (i.e., no VMA). We did find a strong horizontal-vertical asymmetry
135 (HVA), however, in the opposite direction of what is usually found: RM was stronger on the horizontal
136 meridian than on the vertical meridian. Our results show atypical visual field asymmetries in RM. Although
137 related to crowding, these results suggest that RM and crowding have different underlying mechanisms.
138 We suggest that different sensitivities for the extraction of regularity on the vertical and horizontal meridian,
139 and stronger compression of visual space on the horizontal than vertical meridian underlie the observed
140 pattern of results.

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142

143

144 **Methods**

145 *Participants*

146 19 students (age range: 19-47 years, seven male) from the University of Bern participated in the
147 experiment in exchange for course credit or on a voluntary basis. All observers reported normal or
148 corrected-to-normal visual acuity. Observers were naïve regarding the aim of the study. Before the
149 experiment, participants signed a consent form and were informed about the general procedure. The
150 experimental protocols were approved by the local ethics committee at the University of Bern. All
151 procedures were in accordance with the Declaration of Helsinki.

152

153 *Stimuli and Procedure*

154 Stimuli were generated with Psychopy v2.7.11 (Peirce, 2007) and displayed on a 22" CRT monitor
155 with a resolution of 1152 × 864 and a refresh rate of 110 Hz. The experiment was conducted in a dimly
156 illuminated room. Observers viewed the monitor from a distance of 57 cm, and were supported by a chin
157 and head rest. A black disc (diameter=0.2°; 2 cd/m²) at the center of the screen served as a fixation point
158 throughout the experiment. Stimuli consisted of black (1 cd/m²) lines that were 1° in length and 0.04° in
159 width, presented on a uniform grey background (42 cd/m²). The number of presented lines ranged from
160 three to six (Figure 2a). The center-to-center spacing between adjacent lines within a line array was
161 identical, but varied randomly across trials to preclude the use of spacing and overall extent as cues (see
162 example stimuli in Figure 2a). The center-to-center spacing was 0.42°, 0.57°, or 0.85° yielding a maximum
163 extent of the line array of 2.1°, 2.85°, or 4.25°, respectively (when six lines were presented). The lines were
164 arranged radially with respect to fovea, and presented at one of eight cardinal (i.e., left, right, upper, lower)
165 and inter-cardinal (i.e., upper-left, upper-right, lower-left, lower-right) directions (Figure 2b). In total there
166 were 96 (four numbers of lines x three spacings x eight locations) stimulus conditions. The line array was
167 centered at 10° eccentricity. The position of the line array was slightly varied at random across trials
168 (centered at 10° or jittered 0.07° either up, down, left or right).

169 Figure 2c illustrates a schematic depiction of the procedure. At the beginning of the experiment,
170 the fixation disc was presented for 1 s. Observers were instructed to keep fixating on the center. Next, a
171 stimulus was presented for 145 ms at one of eight target locations. Observers were required to indicate the
172 number of lines they perceived with a key press on the number pad (0-9). Observers were not informed
173 about the range of the number of presented lines. Response time was unconstrained. The next trial began
174 454 ms after the response. The stimulus location (eight locations), the number of lines (three to six), and
175 the spacing (0.42°, 0.57°, and 0.85°) were randomized within each block. Observers completed 48 blocks
176 with 80 trials (40 trials for each stimulus condition) with self-paced breaks taken between blocks.

177 Before the experiment, for each participant we verified that the spacing between adjacent lines was
178 above their resolution limit. A two-line discrimination task was performed at the farthest eccentricities of
179 lines in the main experiment (11.7°, when six lines were presented): one or two lines with varying spacings
180 (0.42°, 0.57°, and 0.85°) were presented at the eight locations of the main experiment. Observers were
181 presented with one line in half of the trials, and two lines in the other half. There were 480 trials in total
182 (eight locations x three spacings x ten trials = 240 trials for each number of lines). Participants were asked

183 to indicate whether they perceived one or two lines. Performance was equal to - or above - 95% correct in
184 the majority of trials (87% of the trials; and above 80% correct in the remaining 13% of the trials).

185

186 *Analysis*

187 To assess the strength of RM, deviation scores were calculated by subtracting the correct number
188 of lines from the reported number of lines (Yildirim et al., 2020). Hence, if the number of lines reported was
189 the same as the number of lines presented, the deviation score was zero; reporting more lines than
190 presented yielded scores above zero; and reporting fewer lines than presented yielded scores below zero.
191 When discussing the magnitudes of deviation scores, we refer to absolute values throughout the manuscript
192 (most deviation scores were negative).

193 All statistical analyses were performed in R Studio (version 1.2.5033) running the R software
194 package (version 3.6). The deviation scores were analyzed by a generalized linear mixed-effects model
195 using the glmmTMB package (Brooks, Kristensen, Benthem, Magnusson, Berg, Nielsen, Skaug, Machler,
196 & Bolker, 2017). The number of lines presented, the location of the lines, and the spacing conditions were
197 specified as fixed effects, and subject as a random effect. Predicted values were calculated with the
198 ggpredict function of the ggeffects package (Lüdtke, 2018). The marginal (R^2_m) and conditional (R^2_c)
199 pseudo *R*squared statistics were computed to quantify goodness-of-fit using the r.squaredGLMM() function
200 from the MuMIn package (Barton & Barton, 2015; Johnson, 2014). R^2_m represents the variance explained
201 by fixed effects and R^2_c the variance explained by both fixed and random effects. Assumptions underlying
202 the models were checked with diagnostic plots of residuals using the DHARMA package (Hartig, 2017).
203 Analysis of Deviance Tables (using Type II Wald Chi-Square tests) for the model were calculated using the
204 car package. For significant effects with $p < 0.05$, planned post hoc comparisons were performed with
205 Tukey P adjustment using the emmeans package. Contrasts with $p < 0.05$ were considered as significant
206 (corrected p values are reported).

207 A second-degree polynomial regression was used to fit the deviation scores on the number of lines
208 presented ($R^2_m = 0.17$; $R^2_c = 0.82$). The random effect structure contained random slopes and random
209 intercepts for each subject. The strength of RM varied considerably between observers (but the overall
210 pattern of results was similar across observers, Supplementary Figure 4).

211 To assess the variability of observers' responses, we calculated the standard deviations (SD) of
212 observers' responses for each stimulus location, spacing condition, and number of lines. A three-way
213 repeated measures ANOVA with the factors location, spacing, and number of lines was performed on the
214 SDs of observers' responses. A model without interaction effects was used as the interaction effects were
215 not significant (number of lines and location, $f(21) = 0.81$, $p = .71$; number of lines and spacing, $f(6) = 0.28$,
216 $p = .95$; location and spacing, $f(14) = 0.25$, $p = .99$; number of lines, location, and spacing, $f(42) = 0.17$, p
217 $= 1.0$). ANOVA Tables (using Type II tests) for the model were calculated using the car package. For
218 significant effects with $p < 0.05$, planned post hoc comparisons were performed with Tukey P adjustment

219 using the emmeans package. Contrasts with $p < 0.05$ were considered as significant (corrected p values
220 are reported).

221

222

223 **Results**

224 Mean deviation scores are shown as a function of visual field location in Figure 3. The eight points
225 at cardinal and inter-cardinal directions on the polar plots correspond to the eight target locations. Mean
226 deviation scores ranged between $-0.74 (\pm SE 0.12)$ (strong RM; right horizontal meridian, 6 lines) and 0.1
227 $(\pm SE 0.12)$ (no RM, reporting on average more lines than presented; lower-left location, 4 lines), with clear
228 differences between the different locations. Overall, deviation score magnitudes were larger (i.e., RM was
229 stronger) on the horizontal meridian (left and right visual field) than any other locations (note that 'magnitude'
230 refers to absolute deviation scores; nearly all average deviation scores were negative). We refer to this
231 effect as 'reverse horizontal-vertical meridian asymmetry' (rHVA; apparent in the vertically-elongated and
232 horizontally-compressed patterns in Figure 3). We found a significant main effect of location ($\chi^2(7) = 749.11$,
233 $p < .0001$). Figure 3a shows mean deviation scores averaged over all numbers of lines and spacings as a
234 function of location. Comparisons between each two locations showed that deviation score magnitudes
235 were significantly larger (RM stronger) on the horizontal meridian (left: -0.53 ± 0.10 ; right: -0.59 ± 0.10 ; with
236 no differences between the left and right horizontal meridians (HMA)) than at any other location
237 (Supplementary Table 1a). Deviation scores magnitudes were smaller (but still slightly negative) at the
238 lower-left location (-0.097 ± 0.10) compared to all other locations (except for the lower-right location ($-$
239 0.17 ± 0.10); Supplementary Table 1a).

240 We found significant two-way interactions between location and number of lines ($\chi^2(14) = 41.86$, p
241 < 0.001) and location and spacing ($\chi^2(14) = 110.1$, $p < .0001$). There was no two-way interaction between
242 number of lines and spacing ($\chi^2(4) = 2.98$, $p = 0.56$), and no three-way interaction between number of lines,
243 location, and spacing ($\chi^2(28) = 20.44$, $p = 0.85$). Importantly, significant interactions did not undermine the
244 main effect of location (i.e., rHVA), which holds at nearly all levels of number of lines and spacing (see
245 below). Figure 3b shows the interaction between location and number of lines with mean deviation scores
246 averaged over all spacings. Comparisons between each two locations performed separately for each
247 number of lines showed that the deviation score magnitudes were larger on the horizontal meridian
248 compared to any other location (for all numbers of lines). Figure 3c shows the interaction between location
249 and spacing with mean deviation scores averaged over all numbers of lines. Comparisons between each
250 two locations performed separately for each spacing condition showed that the deviation score magnitudes
251 were larger on the horizontal meridian than at any other location for each spacing (with the exception that
252 there was no difference between the left and the upper location at the largest spacing). These results
253 showed that although visual field location interacted with number of lines and spacing, its main effect, i.e.,
254 rHVA, holds at nearly all levels of number of lines and spacing.

255 We also found significant main effects of the number of lines ($\chi^2(2) = 48.07, p < .0001$) and spacing
256 ($\chi^2(2) = 35.99, p < .0001$). Comparisons between each two numbers of lines showed that the deviation
257 score magnitudes were larger for 3 lines (-0.37 ± 0.096) compared to 4 lines (-0.13 ± 0.11), and 6 lines ($-$
258 0.47 ± 0.12) compared to 4 (-0.13 ± 0.11) and 5 lines (-0.16 ± 0.12) (Supplementary Figure 1a and
259 Supplementary Table 1b). This pattern of deviation scores (larger at the endpoints of the number range,
260 and smaller at the midrange) is consistent with our previous findings (Yildirim et al., 2020). Comparisons
261 between each two spacings showed that the deviation score magnitudes were smaller with the smallest
262 spacing 0.42° (-0.16 ± 0.11) than the other two spacings 0.57° (-0.31 ± 0.10) and 0.85° (-0.38 ± 0.09)
263 (Supplementary Figure 1b and Supplementary Table 1c). These results replicated a trend we found in a
264 previous study where small spacing tended to be associated with slightly weaker RM (Yildirim et al., 2020),
265 possibly because observers used density cues (e.g., Dakin, Greenwood, Kingdom, & Morgan, 2011), and
266 therefore reported larger numbers than with intermediate spacings (at spacings larger than 2.5° at 10°
267 eccentricity, RM ceased, Yildirim et al., 2020).

268 Figure 4 shows the mean deviation scores separately for each number, location, and spacing
269 condition. The deviation scores ranged between $-0.83 (\pm 0.09; \text{right horizontal meridian, 6 lines})$ and 0.28
270 $(\pm 0.16; \text{upper vertical meridian, 5 lines})$. The pattern of results reported above (i.e., different RM with
271 different numbers of lines and different spacings), including the main effect of location, is apparent for the
272 different numbers of lines and spacings: Deviation score magnitudes were larger on the horizontal meridian
273 than at all other locations for each number of lines presented and all spacings.

274 Figure 5 shows summary plots for the (a)symmetries we found (i.e., VMA, HMA, HVA, vertical vs.
275 diagonal meridians, and horizontal vs. diagonal meridians). Deviation scores were averaged over visual
276 field locations and plotted for two different dimensions in each subplot. For example, for the “Horizontal vs.
277 Vertical (HVA)” subplot, the deviation scores of left and right locations vs. lower and upper locations were
278 plotted (illustrating the horizontal vs. vertical asymmetry (HVA)). Deviation of at least one standard error
279 away from the diagonal were considered asymmetries. Asymmetries occurred only for “Horizontal vs.
280 Vertical (HVA)” and “Horizontal vs. Diagonal” comparisons. RM was stronger on the horizontal compared
281 to the vertical and on the horizontal compared to the diagonal meridians. There were no asymmetries
282 between lower vs. upper locations, right vs. left locations, and vertical vs. diagonal meridians.

283 To assess the ambiguity of observers’ percepts at each location, we analyzed the variability of
284 responses by calculating the mean standard deviations (SD; Supplementary Figure 2). There was a main
285 effect of location ($f(7) = 7.52, p < .0001$). Comparisons between each pair of locations showed that SDs for
286 the horizontal meridian were lower than SDs for all other locations (Supplementary Table 2a). There was
287 also a main effect of the number of lines ($f(3) = 21.09, p < .0001$). Comparisons between each two numbers
288 of lines showed that the SD for 3 lines was lower than the SDs for 4, 5, and 6 lines (Supplementary Table
289 2b). Lastly, there was a main effect of spacing ($f(2) = 14.36, p < .0001$). Comparisons between each two
290 spacings showed that SD for 0.42° spacing was higher than SDs for 0.57° and 0.85° spacings, and SD for
291 0.57° spacing was higher than SD for 0.85° spacing (Supplementary Table 2c).

292 Taken together, these results show that RM was stronger (i.e., deviation score magnitudes were
293 larger) and responses were less varied (i.e., SDs were lower) on the horizontal meridian than the other
294 locations.

295
296

297 **Discussion**

298 We investigated whether RM was subject to typical visual field asymmetries. Our results showed
299 that visual field dependencies in RM clearly differed from those in most other visual tasks. RM was stronger
300 on the horizontal meridian than at any other of the tested locations, including the vertical meridian. Hence,
301 we found the opposite of what is typically observed - a “reverse horizontal-vertical asymmetry”. There was
302 also no upper/lower visual field asymmetry: on the vertical meridian, RM was equally strong in the lower
303 and the upper visual field. This pattern of visual field asymmetries suggests that the underlying mechanisms
304 of RM diverge from those of related spatial tasks, including crowding.

305 The typical visual field asymmetries - superior performance on the horizontal than on the vertical
306 meridian (HVA), on the lower vertical than on the upper vertical meridian (VMA), on the right horizontal than
307 on the left horizontal meridian (HMA), and intermediate performance on the intercardinal locations - are
308 well documented for a variety of visual tasks. For example, spatial resolution (e.g., Altpeter et al., 2000;
309 Wertheim, 1894), contrast sensitivity (e.g., Cameron et al., 2002), and spatial localization (e.g., Carrasco
310 et al., 2001) were all shown to be better on the horizontal than on the vertical meridian (HVA), and on the
311 lower vertical than on the upper vertical meridian (VMA). Word and letter recognition were shown to be
312 better on the right horizontal than on the left horizontal meridian (e.g., Hagenbeek, & Van Strien, 2002;
313 Worrall & Coles, 1976; Simola, Holmqvist, & Lindgren, 2009). Performance in orientation discrimination,
314 detection, spatial localization, and contrast sensitivity tasks on the intercardinal locations (upper-right,
315 upper-left, lower-right, and lower-left) was shown to be in between the horizontal and the vertical meridians
316 (Carrasco et al., 2001; Cameron et al., 2002; Carrasco, Giordano, & McElree, 2004). Also for crowding,
317 which shares a number of characteristics with RM, the same typical asymmetries have been reported
318 (Greenwood et al., 2017; He et al., 1996; Kurzawski, Burchell, Thapa, Majaj, Winawer, & Pelli, 2021; Nazir,
319 1992; Petrov & Meleshkevich, 2011a). For example, crowding zones have been shown to be smaller, that
320 is, flankers interfered over smaller distances with target perception, on the horizontal than on the vertical
321 meridian (Greenwood et al., 2017; Kurzawski et al., 2021), on the lower vertical than on the upper vertical
322 meridians (Greenwood et al., 2017; Kurzawski et al., 2021; Petrov & Meleshkevich, 2011a), and on the
323 right horizontal than on the left horizontal meridians (Greenwood et al., 2017; Kurzawski et al., 2021). Thus,
324 our results diverge from typical visual field asymmetries (Altpeter et al., 2000; Barbot et al., 2021; Carrasco
325 et al., 2001; Mackeben, 1999).

326 The effects of RM are most evident when observers do not have to estimate or count the number
327 of items but can subitize them (or see them at a glance; Mandler & Shebo, 1982), i.e., when only very few
328 items (3-4) are presented (Yildirim et al., 2020, 2021). Here, when three lines were presented, deviation
329 scores were -0.56 (± 0.08) on the horizontal meridian (with no difference between the left and right visual

330 field), and $-0.32 (\pm 0.10)$ on the vertical meridian (with no difference between the upper and lower visual
331 field), showing a clear reversal of the horizontal-vertical meridian asymmetry. Importantly, subitizing versus
332 estimating the number of presented items usually differs not only in regard to accuracy but also in regard
333 to observers' confidence. For example, we recently showed that confidence was higher when RM occurred
334 compared to when RM did not occur (Yildirim & Sayim, in revision). With the exact same stimulus (three
335 lines as in the present experiment), observers were more confident when they reported two lines (i.e., RM
336 occurred) than three lines (correct response; no RM). This pattern of confidence judgments was also
337 reflected in the proportion of trials with and without RM: observers reported 2 lines in most of the trials
338 (80%), and 3 and more than 3 lines in the remaining trials (18% and 2%, respectively) (Yildirim & Sayim, in
339 revision). In the present experiment, we did not measure confidence but used the variability of responses
340 to assess the ambiguity of observers' percepts. The variability of responses (SDs, Supplementary Figure
341 2) was smaller on the horizontal meridian compared to all other locations, including the vertical meridian.
342 Particularly, when 3 lines were presented on the horizontal meridian, SDs were smaller than for the other
343 numbers of lines as observers almost exclusively reported 2 (66% of the trials) and 3 lines (26% of the
344 trials; more than three lines in 8%; see Supplementary Figure 3). Hence, it seems that there was not only
345 stronger RM on the horizontal meridian, but also lower ambiguity: Observers perceived less items than
346 were presented and did so comparably consistently.

347 There are several possible reasons for the atypical horizontal-vertical asymmetry we found in RM.
348 First, it could arise from the same underlying mechanisms of tasks that show similar atypical visual field
349 asymmetries. However, it seems that the results found here are uncommon and that the pattern of results
350 found in studies which revealed atypical asymmetries, differed from the pattern we found here. For example,
351 a three-dot bisection task, measuring the ability of spatial localization did not show the typical HVA:
352 performance was similar on the horizontal and vertical meridians (Greenwood et al., 2017). Although the
353 bisection results differed from the typical HVA, they did not resemble the pattern found here, showing how
354 atypical visual field dependencies in spatial vision may vary across tasks. Perceiving the number of items,
355 especially when only a few items are presented, should be closely related to other spatial capacities such
356 as localization (Carrasco et al., 2001) and resolution (Carrasco et al., 2002; Greenwood et al., 2017; Nazir,
357 1992), but there are clear differences regarding their visual field asymmetries, and the relations between
358 the underlying processes remain obscure.

359 One possible explanation is that the pattern of results could be a by-product of a process, such as
360 regularity extraction, that negatively affects enumeration but not related phenomena such as localization
361 and crowding. As noted in the introduction, one of the key factors that determine RM is stimulus regularity.
362 Previously, we found that disrupting the regularity of line patterns by jittering the lines either horizontally or
363 vertically abolished RM (Yildirim et al., 2020). For example, as little as 0.28° of horizontal jitter of a subset
364 of lines, corresponding to 33% of the regular spacing between lines (at 10 degrees eccentricity), was
365 sufficient to abolish RM. Stimulus regularity also determined whether observers reported two or three lines
366 when presented with three equally spaced lines that were slightly tilted to the left or right from vertical

367 (Rummens & Sayim, in revision). When the stimulus was highly regular with all lines of the same tilt
368 direction, observers frequently reported two lines, yielding strong RM; when one line had the opposite tilt
369 direction of the two other lines, no RM occurred (Rummens & Sayim, in revision). Hence, it seems that a
370 certain level of regularity is mandatory for RM. Here, we suggest that any factors that interfere with the
371 extraction of regularity from the presented patterns might also interfere with the occurrence of RM. As
372 perceiving the regularity of the presented line patterns requires accurate (relative) localization of the lines,
373 any interference with accurate localization may as well interfere with the extraction of regularity and
374 therefore reduce or prevent RM, yielding the pattern of results found here. Earlier studies showing superior
375 performance in spatial localization (Carrasco et al., 2001) and regularity extraction (Corballis & Roldan,
376 1975; Jenkins, 1985; Pashler, 1990; Wagemans, Van Gool, & D'ydewalle, 1991) along the horizontal
377 meridian compared to the vertical meridian support this hypothesis. Observers were better at localization
378 tasks when the targets were placed along the horizontal meridian compared to the vertical meridian
379 (Carrasco et al., 2001; Greenwood et al., 2017; Li, Yildirim, Alp, & Sayim, 2021; Smith, 2022). Studies on
380 symmetry perception showed that vertical axis symmetries were more salient compared to horizontal and
381 oblique symmetries (Corballis & Roldan, 1975; Jenkins, 1985; Pashler, 1990; Wagemans, Van Gool, &
382 D'ydewalle, 1991; for reviews see: Wagemans, 1995; Wenderoth, 1994), suggesting that regularity
383 extraction might be better along the horizontal than the vertical meridian. Following this reasoning, strong
384 RM on the horizontal meridian may be partly driven by accurate extraction of the regularity of the line
385 pattern. By contrast, on the vertical meridian, inaccuracies to extract the positions of the individual lines
386 may interfere with the perceived overall regularity of the line arrays. The higher SDs of responses on the
387 vertical compared to horizontal meridian are in line with this interpretation: The inaccuracies of encoding
388 the positions of individual lines may interfere with the perceived regularity of the line array, yielding higher
389 variability of responses. We speculate that such a reduction of the perceived regularity of the line pattern,
390 just as actual irregularities of the stimulus, may underlie the weaker RM on the vertical compared to the
391 horizontal meridian. In addition to stronger RM along the horizontal than the vertical meridian, we also found
392 stronger RM on the horizontal than the diagonal meridians ($\pm 45^\circ$) and no difference between the vertical
393 and diagonal meridians. Stronger RM on the horizontal than the diagonal meridians may similarly be due
394 to superior capacities to extract regularities along the horizontal than the diagonal meridians; however,
395 further studies are needed to better understand the relationship between regularity extraction, visual field
396 dependencies and redundancy masking.

397 A compression of peripheral visual space as found in previous studies could underlie the atypical
398 horizontal-vertical asymmetry in RM. Previous studies have shown that perceptual space is distorted along
399 both the horizontal and vertical meridians in peripheral vision (Osaka, 1977; Sheth & Shimojo, 2001; Wang,
400 Murai, & Whitney, 2020; Yildirim et al., 2019). For example, a target that was briefly presented on the
401 horizontal or vertical meridian was systematically mislocalized as closer to the center of gaze, indicating a
402 compression of visual space between the target and fixation (Sheth & Shimojo, 2001). In another peripheral
403 localization study, observers were asked to fixate a point and to manually point at a target stimulus which

404 appeared briefly at large eccentricities (10° to 50°) along the vertical and horizontal meridians (Osaka,
405 1977). The observers made systematic errors, reporting the target location closer to fixation than its actual
406 location, indicating again that visual space between fixation and the target was compressed. The magnitude
407 of mislocalizations depended on visual field location, with larger mislocalizations seemingly occurring on
408 the horizontal than vertical meridian (Osaka 1977; a significant effect of location, but no comparisons
409 between the locations were reported). In a position matching task, participants indicated the position of a
410 target (shown at 48 different angular positions) with a mouse cursor after the target disappeared (Wang,
411 Murai, & Whitney, 2020). Calculating the angular distance between two adjacent reported locations
412 revealed whether visual space was compressed (when smaller distances were reported) or expanded
413 (when larger distances were reported). It was found that on average visual space was compressed along
414 the horizontal meridian and expanded along the vertical meridian. We found the same pattern of
415 compression along the horizontal meridian in a previous study on RM (Yildirim et al., 2019). In two RM
416 experiments, observers were asked to report the spacing between the two outermost lines (that is, the
417 overall extent of the array) or the spacing between adjacent lines. We found that observers reported the
418 spacing between the outermost of three lines (presented on the horizontal meridian) as smaller than the
419 actual spacing and the spacing between adjacent lines as larger than the actual spacing when RM occurred,
420 but not when no RM occurred (Yildirim et al., 2019). Importantly, the spacing estimations in RM trials were
421 approximately the same in both experiments, indicating that the perceived spacing between the two
422 remaining (of the three presented) lines was similar for two adjacent and the two outermost lines (Yildirim
423 et al., 2019) (In contrast, in 'correct' trials, the spacing between two adjacent lines was accurately estimated
424 while the spacing between the two outermost lines was overestimated). There are two alternative
425 explanations for the observed results: either, one of the outer lines was redundancy-masked, corresponding
426 to an expansion of space, or the central line was masked, corresponding to a compression of space. An
427 experiment assessing the perceived centroid of the line arrays ruled out that an outer line was masked:
428 whether RM occurred or did not occur, observers reported the centroid of the line arrays similarly accurately,
429 indicating the loss of the central line and compression of space in RM (Yildirim et al., 2019). Taken together,
430 we suggest that greater spatial compression on the horizontal meridian compared to the vertical meridian
431 might underlie the reverse horizontal-vertical asymmetry we found in RM. Note that spatial compression
432 and reduced capacities to extract regularities are not mutually exclusive. While it is unclear how the two
433 mechanisms are related, they may well be correlated (strong spatial compression going hand in hand with
434 superior regularity extraction), for example, because of irregular spatial compression. Investigating to what
435 extent regularity perception and spatial compression correlate will shed light on the relation of the two
436 mechanisms.

437 In addition to the horizontal-vertical meridian asymmetry, another important deviation from other
438 visual tasks was the absence of an upper/lower visual field asymmetry (VMA). The typical VMA is
439 characterized by a lower visual field advantage: Performance is usually superior in the lower visual field
440 compared to the upper visual field (Altpeter et al., 2000; Barbot et al., 2021; Carrasco et al., 2001;

441 Greenwood, et al., 2017; Talgar & Carrasco, 2002; but see Previc, 1990; Zito, Cazzoli, Müri, Mosimann, &
442 Nef, 2016 for upper visual field advantages). The VMA has been attributed to higher attentional resolution
443 in the lower compared to the upper visual field (He et al., 1996, 1997; Intriligator & Cavanagh, 2001).
444 According to this explanation, performance for attentionally demanding tasks is better in the lower visual
445 field because of higher attentional resolution in the lower compared to the upper visual field. Consistent
446 with this explanation, a lower visual field advantage in the subitizing range (1-5) was found when observers
447 performed an enumeration task for moving targets among distractors (Lakha & Humphreys, 2005). In
448 contrast, when no distractors were presented, i.e., when targets required no segmentation from distractors,
449 performance was the same in the lower and upper visual fields, suggesting that high attentional demands
450 are required for VMA to occur (Lakha & Humphreys, 2005). The absence of the VMA was also reported in
451 studies investigating orientation discrimination for a single target across the visual field (Kristjánsson &
452 Sigurdardottir, 2008; Zito et al., 2016). For example, a lower visual field advantage was found only when
453 the target was presented among distractors, but not when it was presented in isolation (Kristjánsson &
454 Sigurdardottir, 2008). It was argued that added distractors increased attentional demands of the task,
455 thereby giving rise to the VMA (Kristjánsson & Sigurdardottir, 2008). However, a number of studies also
456 showed the VMA when attentional demands of the task were low (Baldwin, Meese, & Baker, 2012; Cameron
457 et al., 2002; Carrasco et al., 2001), suggesting that the VMA - while it is usually stronger with higher
458 attentional demands - can also occur when attentional demands are relatively low. Taken together, the
459 absence of the VMA in our results may be related to the low attentional demands in enumerating a small
460 number of static lines. The absence of the VMA is also relevant for distinguishing RM from crowding. As
461 mentioned in the introduction, the VMA is a hallmark of crowding (He et al., 1996; He, Cavanagh, &
462 Intriligator, 1997; Intriligator & Cavanagh, 2001). Attentional resolution accounts suggest that crowding
463 occurs due to insufficient resolution of attention, yielding weaker crowding in the lower than in the upper
464 visual field (He et al., 1996; He, Cavanagh, & Intriligator, 1997; Intriligator & Cavanagh, 2001; but see,
465 Fortenbaugh et al., 2015). As we did not find the lower field advantage in RM we suggest that attentional
466 mechanisms play different roles in crowding and RM.

467

468 **Conclusions**

469 To conclude, we found atypical visual field asymmetries in RM: RM was stronger on the horizontal
470 meridian than on the vertical meridian, which is the opposite of the typical horizontal-vertical asymmetry.
471 We also found no evidence for an upper/lower visual field asymmetry: RM was similar in the upper and
472 lower visual field. Our results show that visual field asymmetries in RM diverge from most related perceptual
473 phenomena, including crowding. We suggest that relatively noisy extraction of location information on the
474 vertical compared to the horizontal meridian could contribute to the observed asymmetries: A reduction of
475 perceived regularity may decrease RM and increase ambiguity, yielding the observed pattern of results.
476 Similarly, the atypical visual field asymmetries in RM may be related to a stronger compression of visual
477 space along the horizontal than along the vertical meridian.

478

479 **Data availability**

480 The datasets generated during the study are available on OSF (<https://osf.io/6t4qh/>).

481

482 **Acknowledgments**

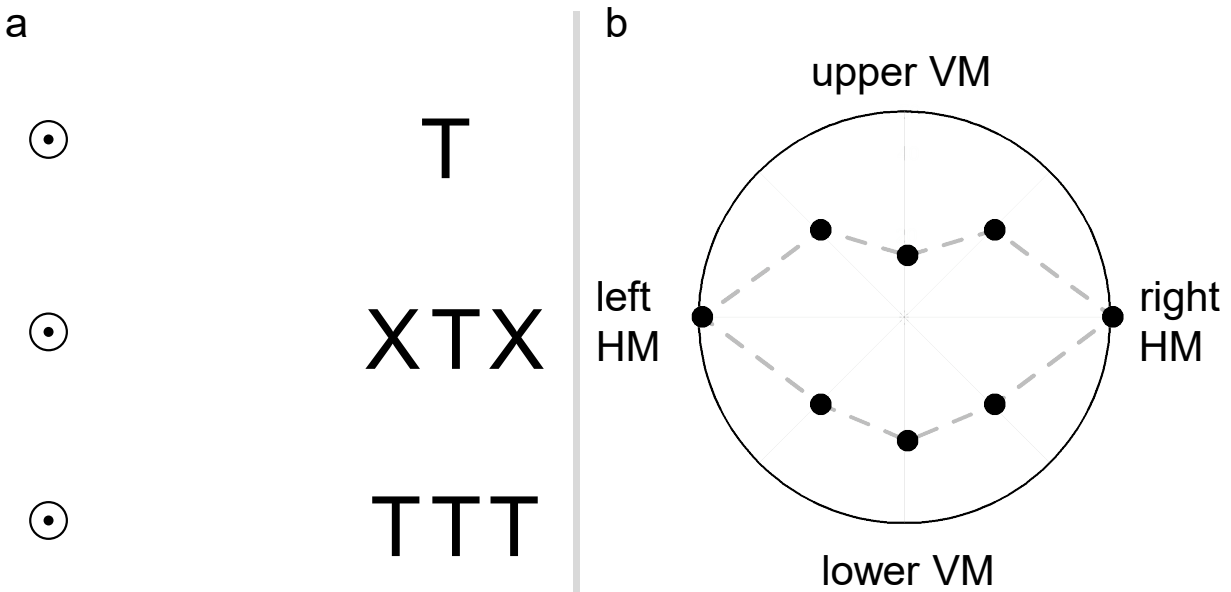
483

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485 Leuven, Belgium. This work was supported by the Swiss National Science Foundation (PP00P1_163723
486 to Bilge Sayim).

487

488

489 **Figure Legends**

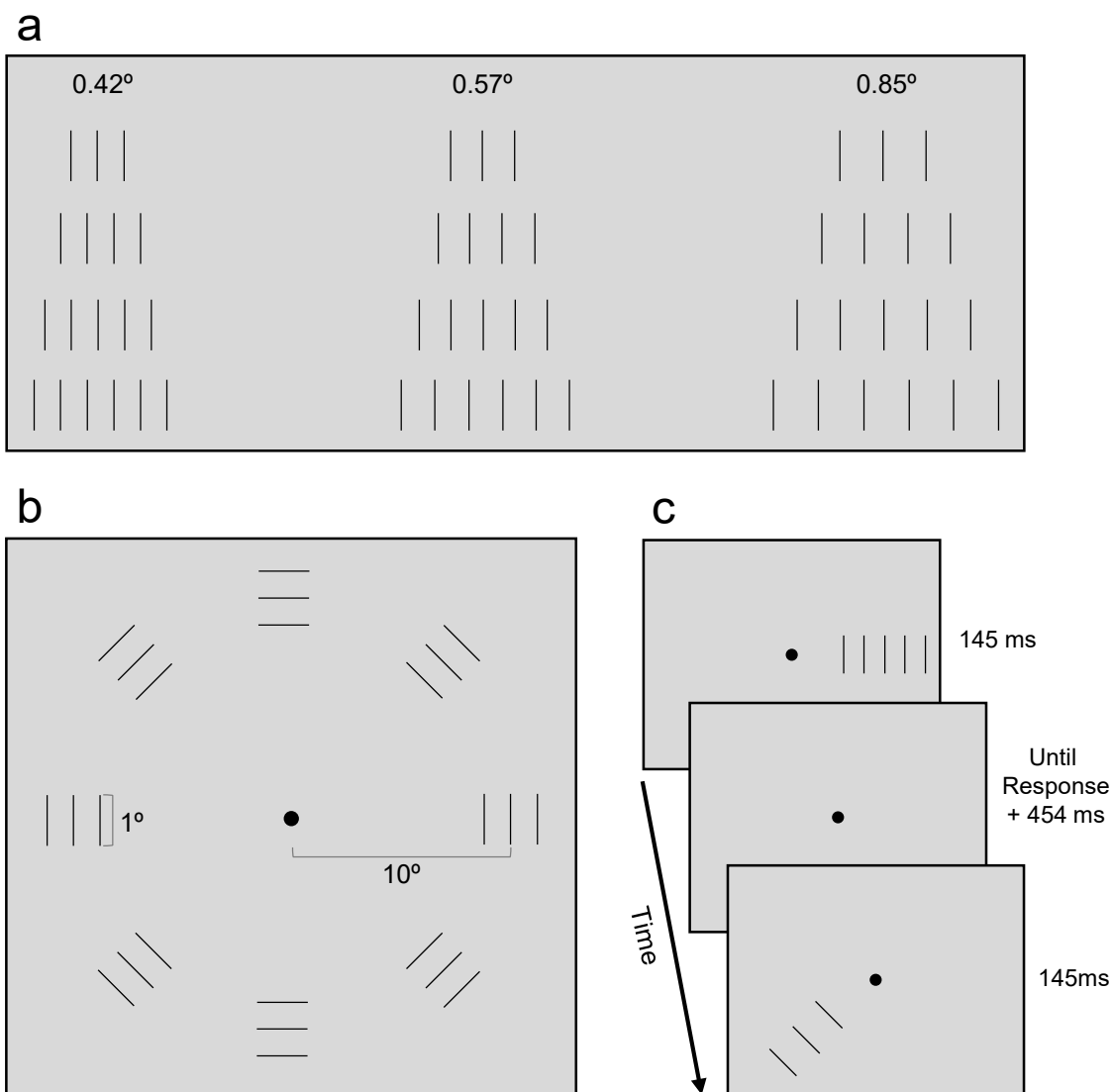


490

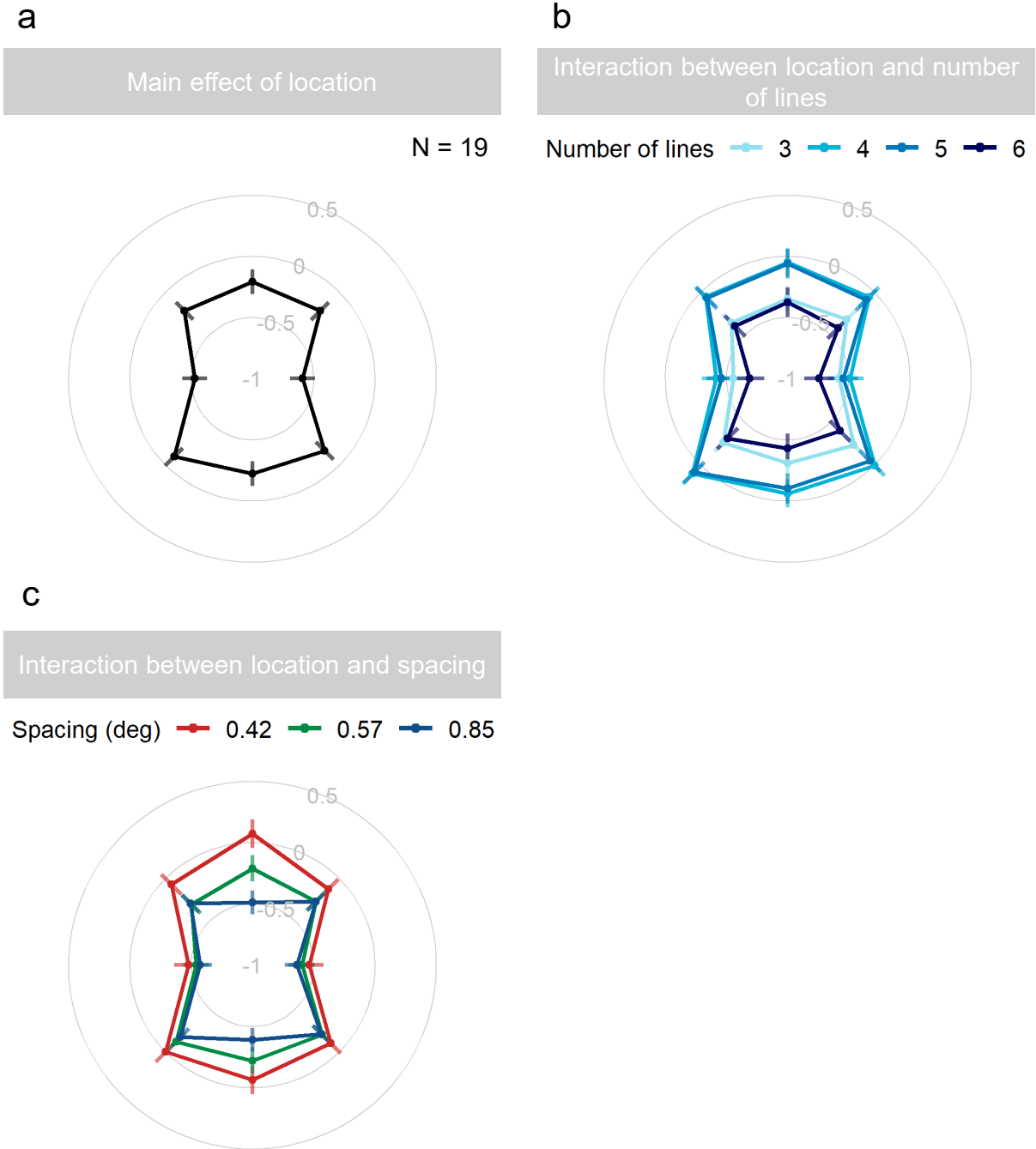
491 **Figure 1.** (a) Illustration of crowding and RM. When fixating the dot on the left, an isolated letter T that is
492 relatively easy to identify (top row) becomes difficult to discern when flanked by nearby letters (middle row;
493 crowding). Observers can identify the repeating letter T (bottom row; RM), but mostly report only two Ts
494 instead of three. (b) Illustration of visual field asymmetries. Each dot denotes performance as a function of
495 polar angle at a fixed eccentricity. The center of the polar plot represents chance level performance. Highest
496 performance is typically observed along the horizontal meridian (HM). Performance on the HM is usually
497 better than on the vertical meridian (VM; horizontal-vertical asymmetry), and better in the lower VM than in
498 the upper VM (vertical meridian asymmetry). Performance along the diagonals ($\pm 45^\circ$) is usually
499 comparable and in between the horizontal and the vertical meridians (Figure adapted from Barbot et al.,
500 2021).

501

502

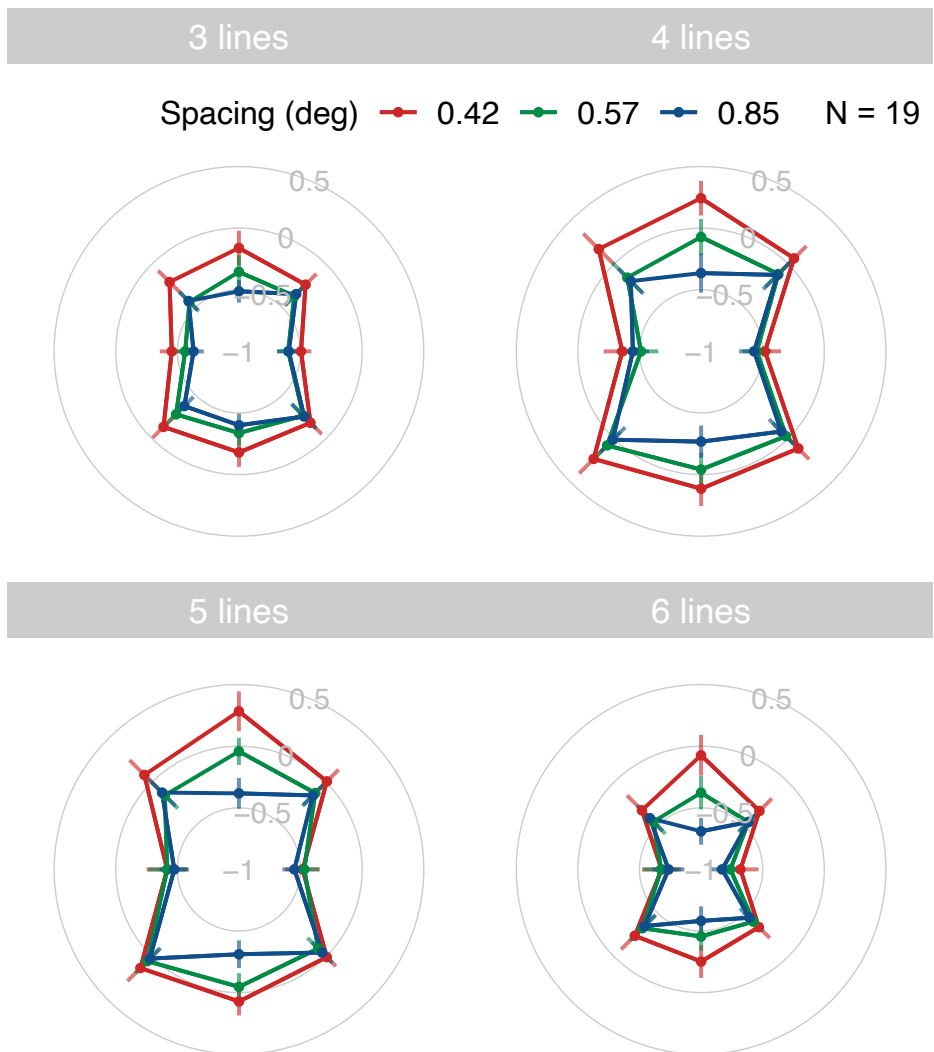


505 **Figure 2.** (a, b) Illustration of the stimuli. (a) Three to six lines with the different spacings (0.42°, 0.57°, and
 506 0.85°). (b) The eight stimulus locations with exemplary stimuli shown at each location (only one stimulus at
 507 a time was presented in the experiment). (c) Schematic depiction of the experimental procedure. (Stimuli
 508 are not drawn to scale).



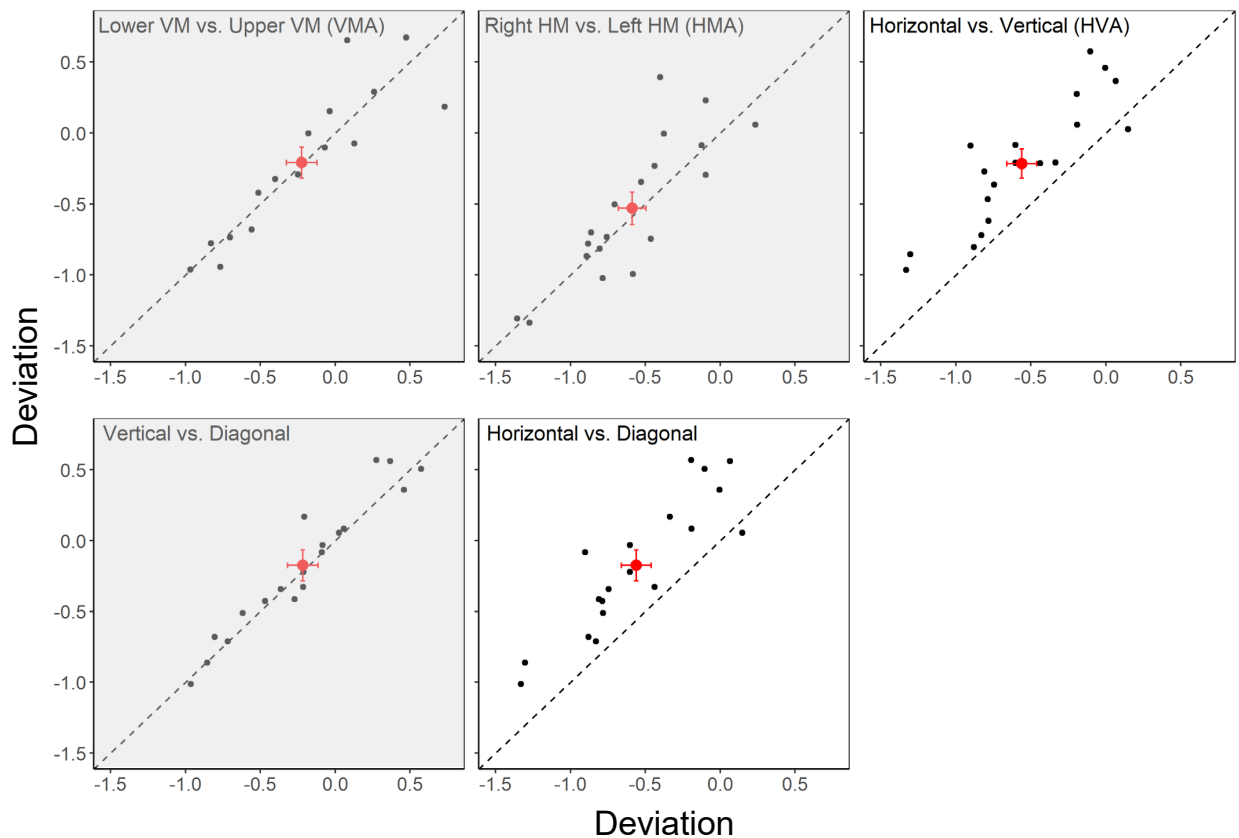
510

511 **Figure 3.** Mean deviation scores averaged over (a) all spacings and number of lines (main effect of
 512 location), (b) all spacings (interaction of location and number of lines), and (c) all number of lines (interaction
 513 of location and spacing) as a function of visual field location. The center of each polar plot (-1) indicates
 514 strong RM (negative deviations scores), 0 indicates correct responses, and the most eccentric polar
 515 coordinate (0.5) indicates overestimation (positive deviations scores). Error bars show \pm SEM. RM was
 516 stronger on the horizontal meridian than all other locations (i.e., rHVA). The rHVA holds at nearly all levels
 517 of number of lines and spacing.
 518



519

520 **Figure 4.** RM as a function of visual field location. Mean deviation scores for each number, location, and
 521 spacing condition are shown in polar coordinates. The center of each polar plot (-1) indicates strong RM
 522 (negative deviations scores) whilst the most eccentric polar coordinate (0.5) indicates an absence of RM
 523 (positive deviations scores). Error bars show \pm SEM. RM was stronger on the horizontal meridian than all
 524 other locations.
 525



526

527 **Figure 5.** Illustration of various (a)symmetries of RM. Deviation scores for different visual fields and axes
 528 are shown in each subplot. The first and second visual field locations in the titles of each subplot denote
 529 the x- and y-axis, respectively. For example, in the “Lower VM vs. Upper VM (VMA)” subplot, lower VM (x-
 530 axis) is plotted with upper VM (y-axis). Each black disk represents the average deviation score of an
 531 individual observer. Points above the diagonal indicate that RM was stronger along the x-axis than the y-
 532 axis; points below the diagonal indicate that RM was stronger along the y-axis than the x-axis. For the (1)
 533 ‘horizontal’, (2) ‘vertical’ and (3) ‘diagonal’ meridians, (1) the ‘left HM and right HM’, (2) the ‘lower VM and
 534 upper VM’, and (3) the ‘lower-right, lower-left, upper-right, and upper-left locations’ were averaged,
 535 respectively. The red disks with error bars (\pm SEM) display the average of all observers. The shaded
 536 subplots show the results for which no asymmetries were observed.

537

538

539

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