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TITLE. [106 characters]

The worse eye revisited: Evaluating the impact of asymmetric peripheral vision loss on everyday function

RUNNING HEAD

The worse eye revisited

PRECIS

Participants performed an everyday visually-guided action (finding a mobile phone) in a virtual-reality domestic environment, while levels of peripheral vision loss were independently manipulated in each eye (gaze-contingent blur). Response time and amount of head- and eye-movements were recorded. The results show that increasing peripheral loss in the *worse* eye diminishes task performance.

TWEET [Max 140 characters incl. tags; Currently 110]

Using #VirtualReality to show how important even an impaired second eye is for performing everyday tasks @Moorfields

AUTHORS

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SUPPLEMENTAL MATERIAL

This article contains one video as additional online-only material. The following should appear online only: ***VRPeripheralVFL.wmv*** (caption: "Screen capture from a single participant, showing the task, the virtual-reality environments, and the simulated loss").

PREVIOUS ORAL PRESENTATION(S) AT SCIENTIFIC MEETINGS

Elements of this work were presented at the Vision Science Society Meeting 2018, St. Pete Beach, Florida, USA.

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CONFLICTS OF INTEREST

No conflicting relationship exists for any author.

NOTES

Figures and Tables are included in the body of this document as low-res screenshots. Publication quality versions of all materials will be uploaded separately as PDFs.

ABSTRACT [206 words; *Max 250*]

1 In instances of asymmetric peripheral vision loss (e.g., glaucoma), binocular performance on
2 simple psychophysical tasks (e.g., static threshold perimetry) is well-predicted by the better seeing
3 eye alone. This suggests that peripheral vision is largely 'better-eye limited'. In the present study,
4 we examine whether this also holds true for real-world tasks, or whether even a degraded fellow
5 eye contributes important information for tasks of daily living. Twelve normally-sighted adults
6 performed an everyday visually-guided action (finding a mobile phone) in a virtual-reality
7 domestic environment, while levels of peripheral vision loss were independently manipulated in
8 each eye (gaze-contingent blur). The results showed that even when vision in the better eye was
9 held constant, participants were significantly slower to locate the target, and made significantly
10 more head- and eye-movements, as peripheral vision loss in the *worse* eye increased. A purely
11 unilateral impairment increased response times by up to 25%, although the effect of bilateral
12 vision loss was much greater (> 200%). These findings indicate that even a degraded fellow eye
13 still contributes important information for performing everyday visually-guided actions. This may
14 have clinical implications for how patients with visual field loss are managed or prioritized, and
15 for our understanding of how visual information in the periphery is integrated.

KEY WORDS: *Peripheral Vision, Psychophysics, Visual Field Loss, Virtual Reality, Eye-tracking, Binocular Vision*

1. INTRODUCTION [Total manuscript length: ~5000 words; Max 6000]

Many common eye-diseases, such as glaucoma and diabetic retinopathy, disproportionately affect peripheral vision. Often, the resultant vision loss is asymmetric, with one eye more badly affected than the other¹. Since in everyday life we tend to view the world binocularly, the better eye may be able to 'compensate' to some degree for the poorer one. Previous data from psychophysical tasks suggest that this compensation is near-total: with binocular perimetric performance almost perfectly predicted by the better eye alone^{2,3}. This implies that peripheral vision is 'better-eye limited': a belief which can have important implications for how patients with asymmetric peripheral vision loss are managed. It is also implicit in common practices, such as the way in which data from monocular eye tests are combined to estimate binocular vision (Integrated Visual Fields)^{4,5}. In general, however, psychophysical measures tend to be poor predictors of real-world performance on vision-related activities of daily living⁶⁻⁸. And it is unclear to what degree this previous finding --- that peripheral vision is 'better eye limited' --- translates from synthetic, psychophysical tasks, to real world judgments involving complex stimuli. In the present study we addressed this question empirically, by asking normally-sighted observers to perform a typical, everyday task (finding a mobile phone in a cluttered domestic scene), while levels of simulated peripheral vision loss were independently manipulated in each eye.

1.1. Background Literature

Evidence for the hypothesis that peripheral vision is 'better-eye limited' comes primarily from psychophysical studies using static threshold perimetry: a common clinical test in which the eye and head is fixed, and detection thresholds are measured for small (~0.5 deg), transient (~200 msec) spots of light, as a function of retinal location. For example, Nelson-Quigg and colleagues (2000)² asked glaucoma patients to perform static threshold perimetry three times: once binocularly, and once with each eye monocularly. They found that at any given location in the visual field, binocular detection thresholds were well predicted by the maximum of the two corresponding monocular thresholds, and that this simple 'best location' method was not significantly less accurate at predicting binocular performance than more complex models in which data from both eyes were summed together (e.g., linear or quadratically⁹). It is possible that some limited binocular summation may have occurred at locations where the sensitivities of the two eyes were very closely matched (relevant analyses not reported). Overall, however, the results indicated that in cases of asymmetric visual field loss, peripheral vision is primarily a function of the better seeing eye alone. Wood and colleagues (1992)³ performed a similar experiment in healthy observers. They found that for foveal targets, binocular sensitivities were approximately $\sqrt{2}$ better

49 than monocular sensitivities (quadratic summation), but that this 'binocular benefit' diminished
50 as a function of eccentricity: becoming near-negligible by 15-30 degrees eccentricity. Older studies
51 from as early as 1931 likewise observed that "there is no summation under conditions of
52 peripheral retinal stimulation when the stimulated area is relatively small"¹⁰.

53 In short, the psychophysical evidence is clear: when it comes to detecting small spots of low-
54 contrast energy, peripheral vision is primarily limited by the better seeing eye, and this is true both
55 in normally sighted people and those with vision loss (glaucoma). Crucially, however, while highly
56 constrained psychophysical paradigms such as static threshold perimetry are ideal for assessing
57 function – and for detecting dysfunction – at the level of the retina, their findings may not generalize
58 to real world tasks, or to higher-order visual judgments. Indeed, even simply increasing the size of
59 a light-spot stimulus has been found to cause rates of binocular integration in the periphery to
60 increase³. Likewise, binocular integration has been found to increase when the stimulus is held
61 constant but the perceptual judgment made more complex (e.g., grating orientation discrimination
62 vs. grating detection)¹¹. It is unknown at present whether the benefits of binocular peripheral
63 vision continue to increase if we move away from synthetic stimuli altogether, and consider the
64 sorts of everyday perceptual judgments that patients report difficulties with most often, such as
65 “finding something on a crowded shelf”, or “noticing an object off to the side”¹².

66 To date, the primary source of evidence regarding everyday perceptual judgments are patient self-
67 reports. Their findings, however, are inconclusive. For example, if peripheral vision is better-eye
68 limited, then scores on vision-related quality of life [VRQoL] questionnaires should be independent
69 of visual field loss severity in the worse eye. However, while visual field loss in the better eye tends
70 to be more strongly correlated with VRQoL¹³⁻²⁵, visual field loss in the worse eye is also correlated
71 with VRQoL^{15,25}, and the difference in explained variance between the two eyes is typically small
72 (i.e., $\Delta R^2 \approx 0.1^{13}$). Furthermore, some studies have failed to replicate even this small difference²⁶
73 (see also ref~[²⁷]). Taken as a whole, these results suggest that peripheral vision is *not* solely a
74 function of the better seeing eye alone, and that the worse eye may also contribute important
75 information. However, it is difficult to draw any firm conclusions from patient self-reports. These
76 studies are not typically intended to examine subtle variations in binocular summation, which may
77 be masked by the intrinsic measurement error of patient self-reports²⁸. Furthermore, vision loss in
78 the better and worse eye is often correlated^{29,30}. Correlations with VRQoL alone also provide only
79 limited insights regarding effect size: how much harder is it, for example, to “find something on a
80 crowded shelf” as vision in the worse eye varies?

81 **1.2. Present Study**

82 To quantitatively assess the ‘real-world’ importance of a worse eye, the present study measured
83 people’s ability to perform a common, everyday visually-guided action (locating a mobile phone in
84 a domestic household scene), while systematically manipulating the level of peripheral vision loss
85 in each eye independently. Instead of examining real patients, gaze-contingent impairments of
86 varying magnitude were digitally simulated in normally-sighted observers. The use of simulations
87 allowed the size, shape and severity of the impairment to be controlled and manipulated precisely
88 in each eye independently. It also meant that each observer could experience every combination of
89 impairments (fully within-subjects design): enabling us to derive a ‘pure’ measure of how vision
90 loss affects performance, independent of individual differences in age, motivation, cognitive
91 function, or overall health. Contrary to the belief that peripheral vision is ‘better-eye-limited’, we
92 hypothesized that performance on a real-world task would diminish (i.e., response times would
93 increase) as peripheral vision loss in the *worse* eye increased. We also analyzed eye- and head-
94 movements to examine whether degrading peripheral vision in one or both eyes caused systematic
95 changes in search behaviors.

96 2. METHODS

97 2.1. Task Overview

98 Participants performed a visual search task in which they attempted to locate a known target (a
99 mobile phone) in various domestic environments, simulated in virtual reality. Levels of peripheral
100 vision loss (blur) were independently manipulated in each eye, trial-by-trial. The question was
101 whether performance (response time, total length of head- and eye-movements) declined as
102 peripheral loss in the worse eye increased.

103 2.2. Participants

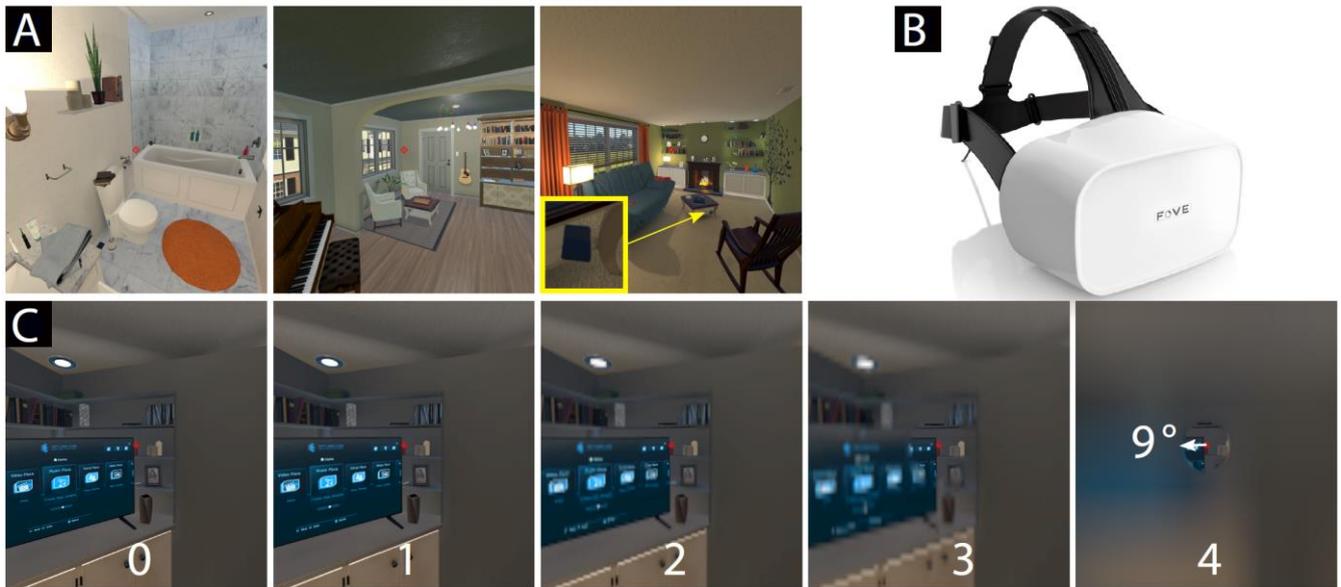
104 Participants were twelve healthy adults (20 – 35 years, $M = 26.2$, $SD = 5.03$), with normal vision.
105 Normal vision was defined as monocular letter acuity ≤ 0.3 logMAR, and no self-reported visual
106 impairments. Written informed consent was obtained prior to testing. The study was approved by
107 host institution's ethics committee (UCL Psychology #11495/001) and was conducted in
108 accordance with the Declaration of Helsinki. Participants received £20 compensation for their time.

109 2.3. Hardware

110 Stimuli were displayed on a FOVE0 Eye-Tracking VR headset (FOVE Inc., San Mateo, CA, United
111 States). This contains a 2560 X 1440 WQHD OLED panel (1280 x 1440 pixels per eye), with a refresh
112 rate of 70Hz and a binocular field of view of approximately 100 degrees. The headset contained
113 two integrated near-infrared eye-trackers (1 per eye) for independently monitoring gaze in each
114 eye, with a single-frame precision of approximately 1 deg, and a refresh rate of 120 Hz. The headset
115 also contained inertial sensors (gyroscope, accelerometer) for monitoring head-pose. There was
116 no crosstalk³¹ between the two eyes, as stimuli --- and simulated impairments --- were presented
117 dichoptically. The software was controlled by a HP OMEN laptop (Hewlett-Packard Company, Palo
118 Alto, CA, United States) containing a NVIDIA GTX 1050Ti graphics card (NVIDIA Corp, Santa Clara,
119 CA, United States).

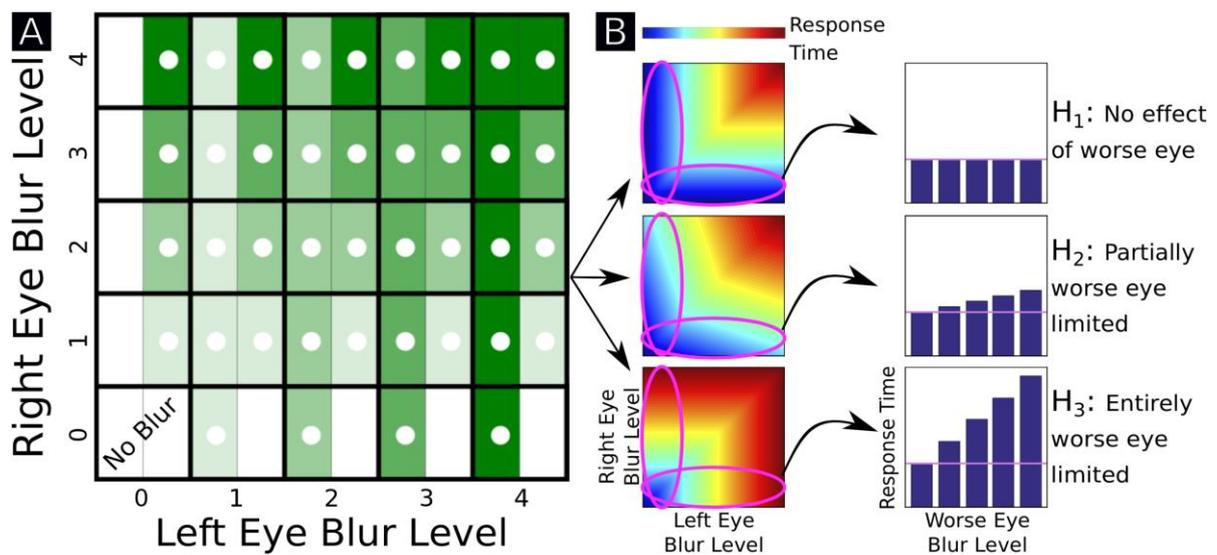
120 2.4. Stimuli

121 The search target was always a black smartphone (Figure 1A, yellow box). The search
122 environments consisted of 15 household rooms (bedrooms, bathrooms, kitchen, etc.), configured
123 into a complete 'suburban' house (see Fig 1A for examples). Depending on the observer's location,
124 it was often possible to see into other rooms, connecting hallways, and the outdoor environ
125 (garden, porch, neighboring houses, etc.). The whole scene was rendered using Unity3D v5.5.2
126 (Unity Technologies ApS, San Francisco, CA, United States), and displayed stereoscopically.



127

128 **Fig 1:** Stimuli and Apparatus. (A) Examples of the 15 search environments, and the target (yellow square). See the Supplemental
 129 Material for a video depicting additional scenes. (B) The F0VE0 head-mounted display, containing independent screens for each
 130 eye, and near-infrared eye-tracking. (C) The five simulated impairment levels (Level 0 = no blur). The Macula was always spared, by
 131 constraining the simulated impairment such that no blur was ever applied to a circular region of radius $\pm 9^\circ$ (white arrow), centered
 132 on the current gaze location (red crosshairs: shown here for illustration only). Note that the observer's gaze was unconstrained
 133 (free viewing), and was tracked in near-real-time using the headset's near-infrared sensor.



134

135 **Fig 2:** Experimental conditions and hypotheses. (A) A 5 x 5 matrix showing the 25 possible combinations of peripheral vision loss.
 136 The intensity of the green shaded regions indicates the magnitude of peripheral loss (blur) in each eye (see Fig 1 for graphical
 137 illustrations of each blur level). (B) Three alternative hypotheses, showing the expected pattern of results if the worse eye: has no
 138 impact on performance (H1); partially impacts performance (H2), or fully determines performance (H3).

139 **2.5. Simulating vision loss**

140 As shown in Fig 1C, the simulated vision loss consisted of a gaze-contingent 'tunnel' of peripheral
141 blur. The retinal location and spatial extent of the blur did not vary, but its magnitude varied trial-
142 by-trial depending on the test condition (see 2.5. *Test Conditions*). A central circular region ($\pm 9^\circ$ in
143 radius, corresponding to the approximate extent of the Macula Lutea), was always spared, meaning
144 that central vision was never impaired.

145 The location of the impairment on the screen was updated in near-real-time based on the
146 participants current gaze location (gaze-contingent presentation), and so remained near-static on
147 the observer's retinae. To make this possible, a rapid blurring algorithm was implemented, which
148 allowed the impairment to be updated well within the screen's refresh rate of 70 Hz without any
149 loss of frames (see below). Inevitably, however, there was a small amount of lag before any changes
150 in gaze could be registered. The lag from the hardware was on the order of ~ 20 msec, and was
151 composed primarily of the Eye Camera exposure time (8 msec), the eye-tracker transmission time
152 (8 msec), and the eye-tracker processing time (4 msec). If we further factor in the refresh rate of
153 the screen (70 Hz) and 3D rendering time, the total expected lag was approximately 30–40 msec.
154 To minimize any effects of eye-tracker calibration drift (i.e., which would cause the location of the
155 simulated field loss to shift over time), the eye-tracker was regularly recalibrated throughout the
156 experiment, as detailed below (2.7. *Procedure*).

157 Blurring was performed in near-real-time using a custom OpenGL fragment shader, which we have
158 made freely available online as part of a general-purpose 'sight loss simulator' toolbox <*methods*
159 *manuscript under review, TO BE UPDATED*>. In short, prior to each screen refresh, a 'pyramid' of
160 progressively more blurred images was created by a repeated process of decimation (box-filtering
161 and downsampling the source image by a power of two). When drawing the image to the screen,
162 pixels were sampled either from the original source image (regions of no blur), and/or were
163 upsampled from this pyramid of decimated images (regions of blur), using trilinear texture filtering
164 to interpolate between pyramid levels as required. This process is generally referred to as
165 mipmapping, and has been detailed previously in the context of simulating visual field loss by Perry
166 and Geisler³² (for further technical specifics on the present implementation, see also Ref~[33]). The
167 key advantage of this method is its computational efficiency, allowing the screen-location of the
168 gaze-contingent blur to be updated with minimal delay (before every screen refresh).

169 The type of blur created by this process is qualitatively similar to a gaussian low-pass filter and
170 would not, for example, have completely removed all higher frequency information. Note also, that
171 this approach is intended primarily as a crude model of retinal loss, such as glaucoma, and was

172 applied as a 'post-processing' effect to the final rasterized image. If attempting to simulate vision
173 loss due to optical defocus, it would also be important to incorporate phase-reversals^{34,35}, and to
174 take into account the distance of each object in the visual scene. The present approach also assumes
175 that observers had negligible refractive error in their periphery, which might otherwise mask the
176 effects of the blur³⁶. This was thought reasonable as a first approximation for our cohort of young,
177 normally-sighted adults. However, even young adults with no foveal refractive error can display
178 large degrees of peripheral astigmatism, with substantial variability between observers³⁷. This
179 assumption may therefore have introduced a degree of noise (or bias) into the present results:
180 error which could be corrected for in future by adjusting analyses to take into account the unique
181 optical characteristics of each observer.

182 Note that blur (low-pass filtering) provided a convenient way to parametrically manipulate the
183 level of vision loss in each eye, and is grossly concordant with the self-reports of glaucoma patients
184 with moderate or advanced field loss: who often describe their vision loss in terms of regions of
185 'blurry' vision³⁸. The use of blur was not intended as a comprehensive simulation of real glaucoma,
186 however. Visual impairments are highly heterogeneous, and often involve other symptoms,
187 including metamorphopsia, a loss of lower frequency contrast, and regions of the field becoming
188 jumbled, missing, or elided³⁹. Likewise, note that the shape of the visual impairment (an extreme
189 'tunnel vision' effect) meant that all regions of peripheral vision were degraded. This is not
190 representative of real glaucoma, which is often irregular and includes regions of spared vision. In
191 future, it may be instructive to explore how covarying the shape of the visual field loss also affects
192 performance. However, this was outside of the scope of the present work.

193 **2.6. Test Conditions**

194 The shape and location of the simulated vision loss was constant. The only free parameter was the
195 magnitude of blur, which on each trial took one of five levels (0,1,...,4), corresponding to a nominal
196 source image widths of 1280 pixels (level 0 – no blur), 640 (level 1), 380 (level 2), 240 (level 3), 20
197 (level 4). To put these values in context, level 4 was sufficiently great that, had it been applied
198 uniformly across the whole visual field of both eyes, the task would be impossible (see
199 *Supplemental Material D*). The level of blur was independently manipulated in each eye, giving a
200 total of 25 (5 x 5) test conditions (see Fig 2A). Each of these 25 test conditions was presented 10
201 times in random order, for a total of 250 trials.

202 **2.7. Procedure**

203 Participants were instructed to "find the phone as quickly as possible". On each trial, one of fifteen
204 rooms was randomly selected, and the target was randomly placed at one of twenty locations

205 within the room: predefined separately for each room. The location and starting orientation of the
206 participant was also randomized, constrained so that the participant was never directly facing the
207 target at trial onset.

208 Throughout the trial, gaze and head-pose were tracked continuously, using the headset's internal
209 near-infrared and gyroscopic sensors, respectively. Participants indicated when they had located
210 the target by pressing a key on a response pad. To avoid errant data from misclicks, a response was
211 confirmed as correct only if the participant's gaze fell within 45° of the target at the time when they
212 pressed the response button. Participants were also monitored by the experimenter throughout
213 via an external computer screen, to ensure they were performing the task correctly. For safety,
214 participants were seated on a rotating office chair, but were free to rotate their head, body, and eyes
215 when searching for the target.

216 The trial ended either when the participant indicated they found the target (by pressing a response
217 button), or after a maximum of 45 seconds had elapsed. The 45-seconds time limit was intended to
218 keep participants motivated throughout testing, and resulted in 104 trials being aborted (~3%).
219 Data from aborted trials are not reported.

220 Each participant completed 250 test trials: 10 trials for each of the 25 test conditions (see *2E. Test*
221 *Conditions*). Participants were encouraged to take a short break every 25 trials (eyes closed with
222 the headset on), and mandatory breaks were given after each 75 trials, during which participants
223 removed the headset. The total testing time, including breaks, was approximately 90 minutes.

224 Before the start of the experiment, and after every break (i.e., a maximum of 75 trials), the eye-
225 tracker was calibrated using the manufacturer-supplied procedure. Each time, the calibration was
226 validated, both by the software's own internal algorithms, and by an informal process of inspection
227 in which the experimenter manually manipulated the location of a target (a red dot), and observed
228 the participant's estimated gaze location. If the headset reported poor calibration, or if the
229 experimenter was not completely satisfied with its accuracy, the calibration was re-run. This
230 happened on ~1% of occasions, generally if the participant physically adjusted the position/straps
231 of the head-mounted display during calibration. During testing, estimated gaze was also visualized
232 on a separate screen, overlaid onto the visual scene. The experimenter monitored this screen for
233 any unusual gaze behavior, and could manually trigger a recalibration. In practice, however, no
234 interventions were required.

235 Before testing participants completed a practice block of 10 trials, designed to familiarize them
 236 with the target, the task, and the various impairment levels. All participants completed these trials
 237 without difficulty (minimum 9 out of 10 correct responses within the time limit).

238 **2.8. Statistical Analysis**

239 The primary question was whether performance varied as vision loss in the worse eye increased
 240 (i.e., after adjusting for individual variability, and for the level of vision in the better eye). To test
 241 this statistically, data were entered into a Linear Mixed-Effects [LME] model, specified, in Wilkinson
 242 (LME) notation⁴⁰, as:

$$y \sim 1 + \text{WORSEYE} + \text{BETTEREYE} + (1 | \text{PARTID}) \quad , \quad (\text{Eq 1a})$$

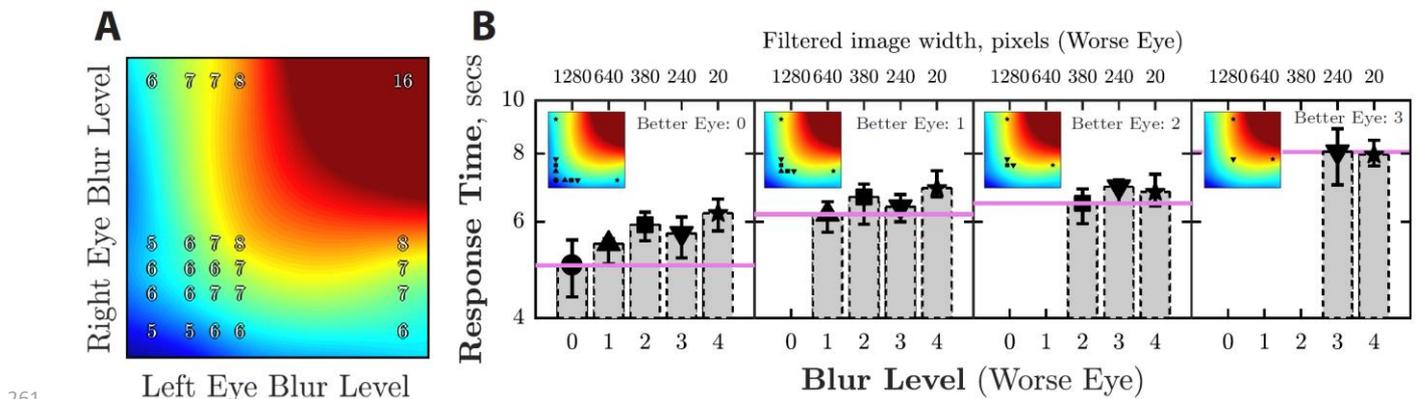
243 where *WORSEYE* was the level of visual impairment (blur) in the worse eye (0 – 100%), *BETTEREYE*
 244 was the level of visual impairment in the better eye (0 – 100%), and *PARTID* was the participant ID
 245 (1 – 12). The dependent variable, *y*, was computed for each trial, and variously took the form: (i)
 246 *log₁₀ Response Time*, in seconds; (ii) *log₁₀ Total Scan-path Length*, in degrees visual angle; (iii) *log₁₀*
 247 *Total Head-turn Length*, in degrees; and (iv) *answer correct* (0 or 1). A significant main effect of
 248 *WORSEYE* would mean that a given outcome measure, *y*, varied as peripheral blur in the worse eye
 249 increased.

250 In practice, the LME model in Eq (1a) was fitted by the MATLAB function “fitlme” (maximum
 251 likelihood method), and the significance of *WORSEYE* predictor variable was formally evaluated
 252 using Simulated Likelihood Ratio Tests⁴¹. Note also that this same model can also be specified in
 253 standard mathematical notation as:

$$y_{im} = \beta_0 + \beta_1 x_{im} + \beta_2 x_{im} + b_{0m} \quad \text{where} \quad b_{0m} \sim N(0, \sigma_0^2) \quad , \quad (\text{Eq 1b})$$

254 where β_0 is the mean intercept, β_1 and β_2 are the predictor variables (Worse/Better Eye), and b_0 is
 255 a random intercept variable which was allowed to vary across the m participants.

256 For all figures and descriptive statistics, data are reported in linear units, using non-parametric
 257 statistics (e.g., medians), and 95% confidence intervals were computed using bootstrapping (N =
 258 20,000; bias-corrected and accelerated method).

259 **3. RESULTS**260 **3.1. Response Time**

261 **Fig 3.** Response time: median time taken to locate the target on each trial, in seconds. **(A)** Heatmap showing median response time
 262 for each condition (see Fig 2A for details regarding conditions). **(B)** Median response time [± 1 S.E.M.], as a function of peripheral
 263 loss in the worse eye. Each panel shows a different level of vision loss in the better eye. Each bar shows a different level of vision
 264 loss in the worse eye (median-averaged across the two corresponding values; i.e., when the left or right eye was the worse eye). For
 265 example, the black square in the first panel is the average response time when peripheral blur in the better eye was Level 0 (no
 266 blur), and peripheral blur in the worse eye was Level 2 (moderate blur in either the left or right eye). As illustrated previously in see
 267 Fig 2B, if the worse eye had no effect on performance then all of the bars within a given panel should fall along the horizontal pink
 268 line.
 269 line.

270 Figure 3 shows how response time varied as the magnitude of peripheral loss in each eye was
 271 manipulated independently. For any given magnitude of loss, performance was degraded more
 272 when the vision loss was bilateral symmetric (i.e., the positive diagonal of Fig 3A), than when it was
 273 applied to one eye only (the bottom row and leftmost column of Fig 3A). For example, when the
 274 impairment was maximal in both eyes (top right point of Fig 3A), grand-median search times across
 275 all participant increased by over 200% (4.9 to 16.0 seconds; Wilcoxon Signed-Rank test; $P < 0.001$).

276 Varying vision loss in the worse eye only (and holding the better eye constant) had a smaller, but
 277 still measurable effect: causing median response times to increase by up to 25% (4.9 vs 6.2 secs;
 278 (Fig 3B). The significance of this effect was confirmed by fitting the LME model in Eq 1a, and
 279 examining the effect of *WORSEEYE* ($t = 2.77$, $P = 0.006$). Taken together, these results indicate that
 280 performance is partially determined by the amount of peripheral vision loss in the worse eye
 281 (hypothesis H_2 in Fig 2). The fact that the worse eye had some effect, but only partially determined
 282 performance, can also be seen intuitively by looking left/right along the bottom row of Fig 3A, and
 283 comparing the pattern of results to the three hypotheses in Fig 2B.

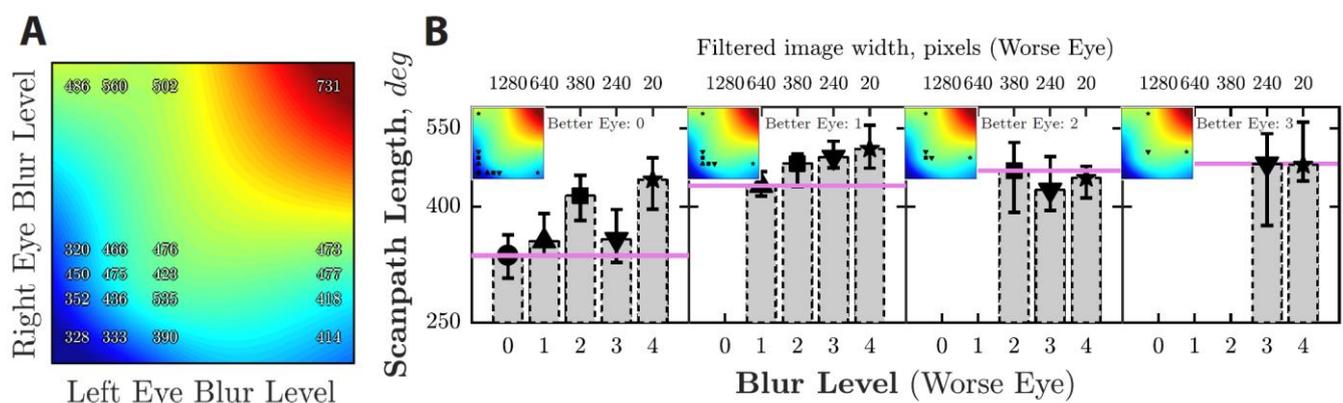
284 Using simple linear regression, it was observed that variations in peripheral vision loss in the worse
 285 eye explained $\sim 2\%$ of the variability in response times ($F = 33.67$, $P \ll 0.001$, $R^2 = 0.017$), versus

286 ~7% for the better eye ($F = 139.9$, $P \ll 0.001$, $R^2 = 0.067$). This confirms that the better eye is the
 287 single greatest predictor of performance, though it is worth noting that vision-loss alone left the
 288 majority of performance-variability unexplained (see also *Supplemental Material A* for further
 289 analysis).

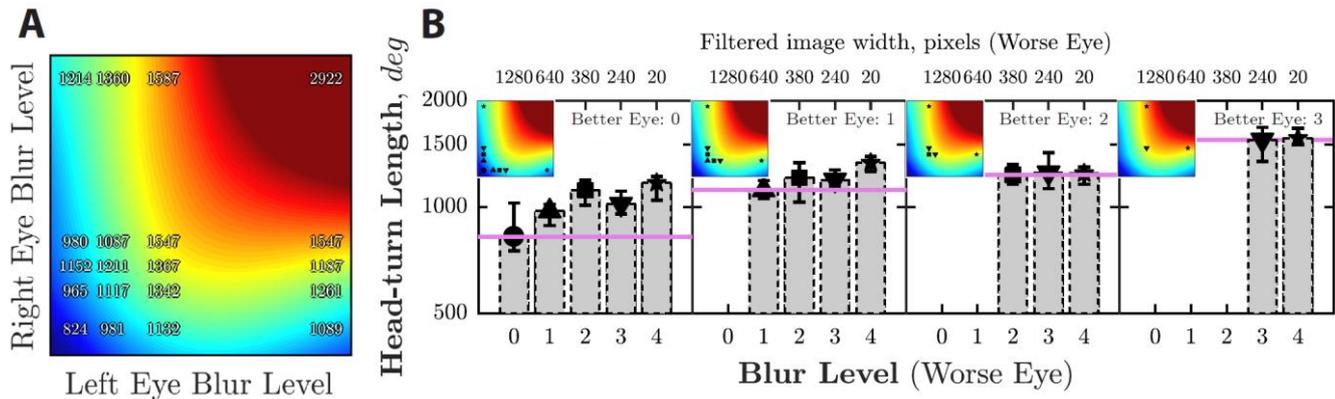
290 By inspection of Figure 3B, it can be seen that there was a possible interaction between the two
 291 eyes: increasing vision loss in the worse eye affected search times most when vision loss in the
 292 better eye was relatively small. To explore this further, post-hoc tests were performed in which the
 293 LME model (Eq 1a) was fitted independently to the data in each of the 4 panels of Figure 3B. The
 294 main effect of *WORSEYE* was significant (*both* $P < 0.05$) in the left two panels (when vision loss in the
 295 better eye was minimal), but was not significant (*both* $P > 0.05$) in the right two panels (when
 296 vision loss in the better eye was moderate or severe). This indicates that vision loss in the worse
 297 eye may be an important factor only when the better eye is relatively healthy.

298 3.2. Eye- and Head-Movements

299 The amount that participants moved their eyes (Fig 4) and head (Fig 5) when searching for the
 300 target exhibited the same pattern of results as the response time data (Fig 2B). Thus, participants
 301 made more searching movements as vision loss in the *worse* eye increased, and this effect was
 302 statistically significant for both eye-movements ($t = 2.1$, $P = 0.016$) and head-movements ($t = 2.8$, P
 303 $= 0.005$). Again, there was also an interaction between the two eyes, with post-hoc tests indicated
 304 that the effect of *WORSEYE* was significant only when vision loss in the better eye was minimal (the
 305 first two panels of Fig 4A/5A; *all* $P < 0.05$). Overall, these results provide convergent evidence that
 306 peripheral loss in the worse eye substantively affects task performance, particularly when the
 307 fellow (better) eye is relatively healthy.



308
 309 **Fig 4.** Median scanpath length (amount of eye-movements) on each trial, in degrees. Same format as Figure 3.



310
311 **Fig 5.** Median head-turn length (amount of head-movements) on each trial, in degrees. Same format as Figure 3.

312 **3.3. Response Accuracy**

313 Response accuracy (percent correct responses) did not change across any of the visual impairment
 314 conditions, and was close to 100% throughout ($M = 96\%$; see *Supplemental Material B*). Thus, there
 315 was no effect of *WORSE EYE* when the mixed-effects analysis was run ($t = -0.07, P = 0.944$), and in fact
 316 a one-way ANOVA found no significant difference in percent-correct responses between any of the
 317 25 impairment conditions ($F = 0.04, P = 0.340$). This indicates that while peripheral vision loss
 318 caused participants to be slower in locating the target, they were no more likely to mistake the
 319 target for another object. This is to be expected, given that central vision in both eyes was spared.

320 4. DISCUSSION

321 The results showed that participants were slower to find an everyday object in a cluttered domestic
322 scene --- and made more head and eye movements when searching --- as simulated peripheral
323 vision loss in the *worse* eye increased: even when vision in the better eye remained constant. This
324 indicates that for everyday visually-guided tasks, peripheral vision is not 'better-eye limited', and
325 that the worse eye also provides important information for daily living. The benefit of the worse
326 eye was greatest when vision in the better eye was relatively healthy, suggesting that the
327 preservation of fellow-eye vision may be most important in early-to-moderate cases of field loss.

328 Substantial trial-by-trial variability in performance was apparent, as indicated by the large error
329 bars in Figures 3–5, and by the relatively small amount of response variability explained by sight
330 loss alone. This is to be expected given the relatively uncontrolled task: No concerted attempt was
331 made to match search-environments/target-locations for difficulty, and it is highly likely that the
332 phone was objectively easier to locate on some trials (e.g., because some rooms contained fewer
333 likely locations, or because the visual dissimilarity of target vs background was greater). The fact
334 that there was a clear and consistent overall pattern to the data, *despite* this lack of complete
335 stimulus/experimental control, we take as particularly good evidence that the reported effect is
336 genuine and has substantive real-world implications. Notably, it is possible to contrive stimuli for
337 which the present effects are greater and more consistent than those observed here. For example,
338 we report in *Supplemental Material C* a variant of the present task in which the target and
339 environments were random textures, and where the effect of degrading the worse eye was much
340 greater. Such task-variants could be of interest for people looking to adapt the present paradigm
341 to detect or quantify visual impairment.

342 4.1. Comparison with Previous Literature

343 The present data stand in contrast to previous findings using more basic psychophysical tasks
344 (static threshold perimetry), on which binocular sensitivity in the periphery is largely predicted
345 by the better eye alone^{2,3}. This mismatch highlights that basic psychophysical tasks do not always
346 provide a perfect model of an individual's ability to perform 'real world' perceptual judgments: a
347 fact which has also been widely reported previously, particularly in the context of visual acuity⁶⁻⁸
348 and visual field loss⁴²⁻⁴⁴. The present findings are, however, broadly consistent with qualitative
349 clinical data. For example, several studies have reported reductions in visual disability and
350 symptoms following second-eye cataract surgery, despite often minimal changes in acuity^{45,46}. One
351 corollary of this is that we may in future need to move away from purely 'synthetic' stimuli, such

352 as light-spots, gratings, or isolated optotypes, if we wish to fully characterize the functional impact
353 of sight loss.

354 The fact that eye-movements increased with increasing peripheral loss is consistent with a number
355 of previous studies examining the natural eye-movements of glaucoma patients^{1,47-49}. To our
356 knowledge, only one study by Dive et al. (2016)⁴⁹ has examined head movements in glaucoma
357 patients. They likewise reported elevated levels when performing 'real world' tasks, although no
358 quantitative data were reported. The present study confirms these observations by providing
359 direct, simultaneous measurements of head- and eye-movement under conditions of simulated
360 peripheral vision loss. It is interesting to note that in the present study, the observed changes in
361 head-movements were at least as great as the changes in eye-movements. This suggests that head-
362 movements might provide a possible biomarker for the detection of eye-disease --- as has been
363 suggested previously for eye-movements¹. The next important step will be to test this possibility
364 empirically. The present study also demonstrates the sorts of new insights that can be achieved by
365 moving away from 'traditional' visual assessments in which the eye and/or head is constrained by
366 fixation targets and chinrests.

367 **4.2. Limitations**

368 The present study employed simulated impairments, rather than real patients. This was necessary,
369 as it allowed us to systematically manipulate the impairment and to control for individual
370 differences. It does, however, mean that we have to interpret the results with caution. To the extent
371 that real eye-disease may cause not just high frequency loss (blur), but also a range of other
372 disturbances (low frequency loss, spatial distortions, chromatic anomalies, crowding, infilling,
373 etc.), the worse eye may play an even greater or smaller role than was observed here. Notably, the
374 simulator used in the present study is also capable of incorporating many of these other effects,
375 and these effects can be linked to empirical data from real patients³³. It would therefore be possible
376 in future to conduct a more comprehensive assessment of how different forms of vision loss affect
377 everyday visually-guided actions, or a detailed analysis of how a particular individual's visual
378 profile affects daily living. These would be non-trivial undertakings, but the code for the present
379 simulations has been made freely available online for anybody interested in pursuing this line of
380 inquiry <methods manuscript under review, TO BE UPDATED>. It likewise remains an open question
381 whether performance would change over time as the individual learns to adapt to their impairment
382 – a consideration which may be particularly relevant to diseases such as glaucoma, where sight loss
383 is often gradual and progressive. The question of adaptation could be explored in future empirically

384 – for example through the use of Augmented Reality simulations, which in principle can be worn
385 for days or weeks at a time.

386 The present data demonstrated that peripheral sight loss affects binocular performance on
387 everyday visual-guided tasks, even when the loss is unilateral. However, they do not tell us how or
388 by what means the worse eye contributes task-relevant information. One possibility is that the
389 change in performance was due primarily to an overall loss of (contrast) sensitivity. Normal vision
390 is comprised of a central binocular field, and two unocular flankers⁵⁰. By adding blur to the
391 periphery of one eye, the binocular field is shrunken/decreased, limiting opportunities for
392 binocular summation, while one of the flanking regions is lost altogether, effectively narrowing the
393 total field of view. The result is a narrower, shorter 'hill of vision'. In addition to overall changes in
394 sensitivity, however, disrupting binocular vision through the addition of monocular blur can also
395 have secondary consequences, including aberrant motion processing⁵¹ and a loss of (high-
396 frequency) stereopsis⁵². The latter is particularly significant for the present task (Visual Search),
397 since stereopsis is known to be important for 'breaking camouflage'⁵³, while the former may have
398 similar consequences by removing another important depth cue: motion parallax. From the
399 present study, it is not possible to determine which, if any, of these factors are important for
400 explaining the pattern of results observed. In future, however, such questions could be explored
401 experimentally by modifying the present paradigm. For example, instead of applying blur one could
402 selectively remove binocular disparity from the periphery of both eyes. Alternatively, participants
403 could view a 2D plane instead of a 3D environment, to further remove motion parallax cues. To the
404 extent that the same pattern of results continued to hold, it would indicate that it is these secondary
405 depth cues, rather than a loss of sensitivity, that are primarily responsible for changes in
406 performance observed.

407 A further limitation of the present study is that the central macula region of $\pm 9^\circ$ was always spared.
408 We are therefore unable to infer what the effect of unilateral loss would be if this 'healthy' region
409 were reduced. The benefits of binocular summation in central vision are, however, well-
410 established, with previous studies showing that observers are better at detecting faint objects⁵⁴,
411 resolving fine spatial detail^{55,56}, or performing delicate visuomotor actions⁵⁷, when fixating with
412 two foveae versus just one. We therefore predict that the preservation of the fellow-eye would be
413 at least as beneficial in instances of central or paracentral vision loss. Consistent with this, the same
414 qualitative pattern of results as reported here was observed in a small cohort of observers when
415 the blur was applied uniformly across the whole visual field (see *Supplemental Material D*).

416 **4.3. Implications & Future Work**

417 The present study indicates that there may be a real-world cost to unilateral peripheral vision loss
418 that is not captured by traditional psychophysical measures, such as static threshold perimetry.
419 Such deficits could have particular implications for time-critical tasks, such as driving. Thus, if we
420 consider the conditions involving a purely unilateral impairment (the leftmost panel of Figures 3–
421 5B): such individuals would be expected to score near-perfectly on a standard binocular visual
422 field assessment^{2,3,10}. They would therefore be considered legally fit to drive in most countries,
423 even professionally⁵⁸. In contrast, such individuals were 1 second (25%) slower, on average, to
424 locate the target object (and on some trials much slower). To put this in context, when driving at
425 ~30 mph (~50 km/h), an additional 1 second delay in braking is enough to increase stopping
426 distance by 40%⁵⁹, and double the likelihood of severely injuring a pedestrian three car-lengths in
427 front⁶⁰. This is particularly concerning given that individuals with unilateral glaucoma are no more
428 likely than their normally-sighted peers to cease driving⁶¹. At present, we can of course only
429 speculate precisely how the present results would translate to other real-world scenarios, such as
430 driving. It may be, for example, that some drivers can compensate for their vision loss through
431 increased vigilance⁶² (though see ref~[⁶³]). Notably, the technologies developed for the present
432 work are compatible with all modern software and hardware devices. It would therefore be
433 possible to apply the same simulated impairments to existing driving simulators, and to observe
434 empirically their effects on performance.

435 More generally, the present work highlights the importance of measuring not only response
436 accuracy, but also response speed and effort, when characterizing a visual impairment. Thus,
437 compared to healthy vision, even an intense, bilateral simulated impairment caused no significant
438 change in response accuracy, which was close to 100% throughout. It did, however, cause response
439 times to be significantly slower (by over 200%, in the bilateral-symmetric case), and compelled
440 participants to make substantially more head- and eye-movements. These findings echo a recent
441 report by Barsingerhorn and colleagues⁶⁴, who observed that children with ocular dysfunction
442 were slower at performing a simple spatial judgment (landolt-C orientation-identification) than
443 their normal-sighted peers, even after the stimuli were matched in size for relative acuity. Taken
444 together, such findings suggest that when characterizing vision loss, it may be prudent to move
445 beyond simple functional measures of accuracy. It may, for example, be desirable to consider a
446 treatment effective if it makes visual judgments faster or less tiring, even if there is no substantive
447 change in the size or contrast of the smallest identifiable object. It is interesting to note that this is
448 already an established principle in the auditory community, where fatigue, effort and stress are

449 considered when evaluating hearing impairment⁶⁵. Such constructs are difficult to quantify using
450 traditional ‘pen and paper’ vision tests, but can be more easily probed using the sorts of digital
451 technologies reported here.

452 Finally then, the present study highlights the potential utility of Virtual- and Augmented-Reality
453 simulations for assessing the real-world impact of visual impairments. As discussed previously,
454 traditional measures of visual function, such as acuity and visual field loss, typically explain only a
455 minority (10 – 30%⁴²⁻⁴⁴) of the variability in self-reported vision related quality of life. In contrast,
456 functional evaluations in real-life scenarios such as driving are difficult to obtain, and sometimes
457 even dangerous. VR technologies such as those presented here may provide a novel platform with
458 which to observe directly a person’s ability to perform key everyday tasks, and to do so in a way
459 that is controlled, quantifiable, replicable, and safe. Notably, however, substantial hardware
460 development is still required before VR technology will be suitable for most patients. This includes
461 the development of lighter, more comfortable headsets, and the ability to integrate appropriate
462 refractive correction across a wide range of prescriptions.

463 **4.4. Summary and Conclusions**

- 464 1. Varying degrees of simulated peripheral vision loss (blur) were applied to one or both eyes
465 of twelve normally-sighted adults.
- 466 2. Participants were slower to find an everyday object in a cluttered domestic scene --- and
467 made more head- and eye-movements when searching --- as peripheral vision loss in the
468 *worse* eye increased. This suggests that peripheral vision is not entirely ‘better-eye limited’,
469 and that even the *worse* eye contributes important information for performing activities of
470 daily living.
- 471 3. More generally, the data suggest that simple synthetic tasks may not always be sufficient to
472 fully-characterize visual impairments, and that VR technologies might in future provide a
473 productive tool with which to observe and quantify the everyday impact of vision loss.

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651 **Supplemental Material** [This section will be reformatted as a separate document if/as required]

652 **A. Supplemental Analysis: The relative importance of the better vs worse eye**

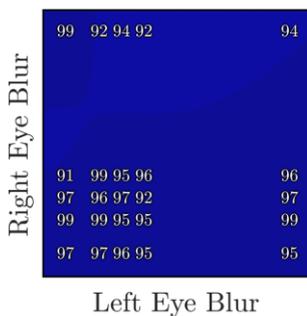
653 To determine whether performance was closer to H_1 (entirely better eye, BE, driven) or H_3 (entirely
 654 worse eye, WE, driven) the following simple analysis was performed. Consider responses times, RT ,
 655 in the extreme unilateral case (WE: Lvl 4, BE: Lvl 0), the extreme bilateral case (WE: Lvl 4, BE: Lvl
 656 4), and the no impairment case (WE: Lvl 0, BE: Lvl 0). The relative weight given to the worse eye,
 657 ω_{WE} , should be given by:

$$\omega_{WE} = \frac{RT_{unilateral} - RT_{no\ imp}}{RT_{bilateral} - RT_{no\ imp}} \quad (\text{Eq S1})$$

658 If $\omega_{WE} = 1$ (i.e., no difference in RT between unilateral and bilateral impairment) then it implies that
 659 performance was entirely determined by the worse eye. If $\omega_{WE} = 0$ then performance was entirely
 660 determined by the better eye. If $\omega_{WE} = 0.5$ then both eyes were equally important. In practice, ω_{WE}
 661 = 0.11, which indicates that the better eye was the greatest single predictor of performance.

662 **B. Supplemental Analysis: Effect of peripheral loss on response accuracy (percent correct)**

663 As shown in Fig S1, response accuracy (percent correct responses) did not vary systematically
 664 across any of the peripheral impairment conditions. See main manuscript for statistical analysis.



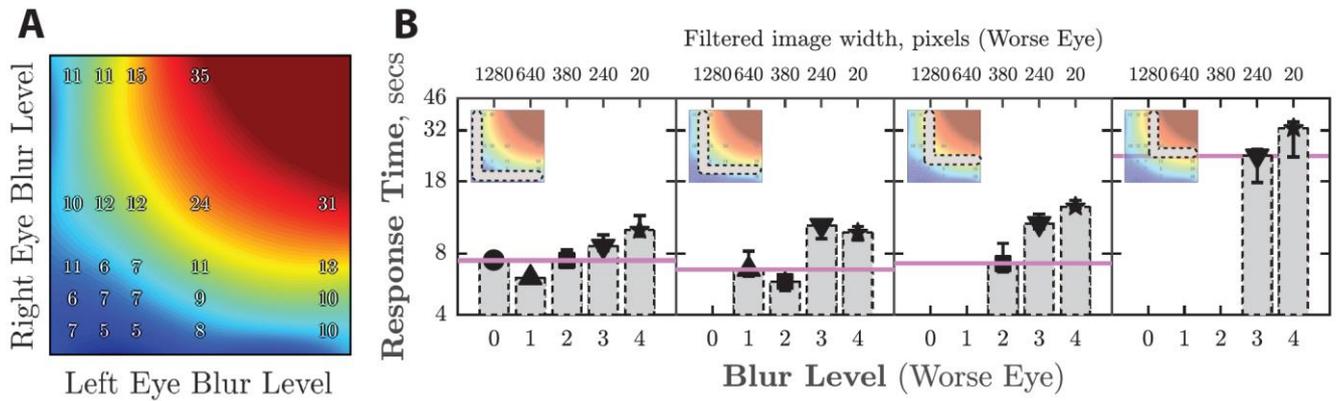
665 Left Eye Blur
 666 **Fig S1.** Response accuracy: percent correct responses as a function of left eye impairment level (abscissa) and right eye impairment
 667 level (ordinate).

668 **C. Supplemental Experiment: Texture-in-texture search task**

669 Figures S2 and S3 shows data from five new participants, who performed a variant of the main
 670 task, in which the target was convex textured hemisphere, presented against a concave textured
 671 background (see Fig S2 for depiction of the stimuli). In that case, the overall pattern of results was
 672 the same as in the present study, but the effects were larger in absolute terms (note the different
 673 y-axis scale in Fig S3 compared Figures 3–5 of the main manuscript) and were apparent even in a
 674 small cohort of participants ($N=5$). That such stimuli elicit a greater and more consistent ‘worse
 675 eye’ effect is to be expected, given that the target included a strong stereoscopic depth cue, and all
 676 non-perceptual confounds were removed. This task-variant could therefore be of interest for
 677 people looking to adapt the present paradigm to detect or quantify visual impairment.



678 **Fig S2.** Example stimuli (left-eye/right-eye) for a pilot ‘texture search’ variant of the main task, in which the target and search
 679 environment were replaced with patterns of random noise. Impairments are not shown, but consisted of variable blur similar to
 680 that illustrated in Fig 1 of the main manuscript. The target (convex textured hemisphere) is circled in yellow for visualization
 681 purpose.
 682

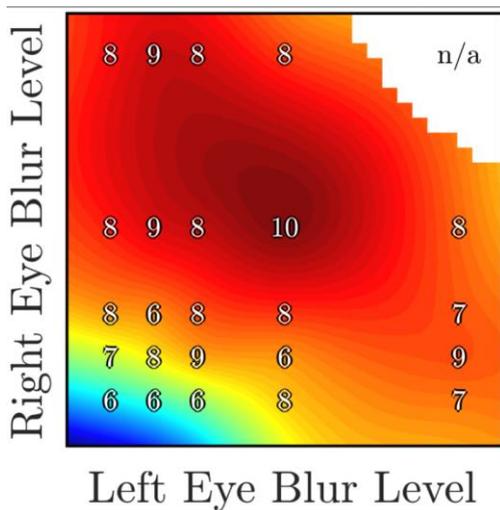


683

684 **Fig S3.** Response time data for a pilot ‘texture search’ variant of the main task (see Fig S2 for stimuli). These data are analogous to
 685 the those shown previously in Figure 3 (main manuscript), and exhibit a similar overall pattern. In this case, however, data are from
 686 5 participants only, and the size of the main effect (parameter *WORSEYE* in Eq 1) was even more clearly significant: $t = 8.72$, $P \ll$
 687 0.001 [$P = 1e-17$].

688 **D. Supplemental Experiment: Uniform blur condition**

689 Figures S4 shows data from five new participants, who performed the exact same task to the main
 690 study, but with uniform blur (no central spared region). Compared with the peripheral-only blur
 691 (Figure 3A of *Main Manuscript*), the data showed a qualitatively similar pattern of results, although
 692 --- unsurprisingly --- the blur had an even greater detrimental effect on performance at all
 693 magnitudes. Furthermore, in the highest blur level, the task became impossible when the blur was
 694 bilateral symmetric (top right of Fig S4).



695

696 **Fig S4.** Response time data for a “uniform blur” variant of the main experiment. These data are analogous to the those shown
 697 previously in Figure 3A (*Main Manuscript*).