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

Hugo Chow-Wing-Bom[1], Tessa M. Dekker[1], Pete R. Jones[1,2]

[1]*Institute of Ophthalmology, University College London (UCL), London, United Kingdom*
[2]*National Institute for Health Research Moorfields Biomedical Research Centre, London, United Kingdom*

CORRESPONDENCE

Pete R. Jones; Institute of Ophthalmology, University College London, 11-43 Bath Street, London EC1V 9EL; p.r.jones@ucl.ac.uk

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

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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*]

In instances of asymmetric peripheral vision loss (e.g., glaucoma), binocular performance on simple psychophysical tasks (e.g., static threshold perimetry) is well-predicted by the better seeing eye alone. This suggests that peripheral vision is largely 'better-eye limited'. In the present study, we examine whether this also holds true for real-world tasks, or whether even a degraded fellow eye contributes important information for tasks of daily living. Twelve normally-sighted adults 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). The results showed that even when vision in the better eye was held constant, participants were slower to locate the target, and made more head- and eye-movements, as peripheral vision loss in the *worse* eye increased (*all* P < 0.001). A purely unilateral impairment increased response times by up to 25%, although the effect of bilateral vision loss was much greater (> 200%). These findings indicate that even a degraded fellow eye still contributes important information for performing everyday visually-guided actions. This may have clinical implications for how patients with visual field loss are managed or prioritized, and 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 other[1]. 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 living[6–8]. 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 quadratically[9]). 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 than monocular sensitivities (quadratic summation), but that this 'binocular benefit' diminished as a function of eccentricity: becoming near-negligible by 15-30 degrees eccentricity. Older studies from as early as 1931 likewise observed that "there is no summation under conditions of peripheral retinal stimulation when the stimulated area is relatively small"[10].

In short, the psychophysical evidence is clear: when it comes to detecting small spots of low-contrast energy, peripheral vision is primarily limited by the better seeing eye, and this is true both in normally sighted people and those with vision loss (glaucoma). Crucially, however, while highly constrained psychophysical paradigms such as static threshold perimetry are ideal for assessing function – and for detecting dysfunction – at the level of the retina, their findings may not generalize to real world tasks, or to higher-order visual judgments. Indeed, even simply increasing the size of a light-spot stimulus has been found to cause rates of binocular integration in the periphery to increase[3]. Likewise, binocular integration has been found to increase when the stimulus is held constant but the perceptual judgment made more complex (e.g., grating orientation discrimination vs. grating detection)[11]. It is unknown at present whether the benefits of binocular peripheral vision continue to increase if we move away from synthetic stimuli altogether, and consider the sorts of everyday perceptual judgments that patients report difficulties with most often, such as “finding something on a crowded shelf”, or “noticing an object off to the side”[12].

To date, the primary source of evidence regarding everyday perceptual judgments are patient self-reports. Their findings, however, are inconclusive. For example, if peripheral vision is better-eye limited, then scores on vision-related quality of life [VRQoL] questionnaires should be independent of visual field loss severity in the worse eye. However, while visual field loss in the better eye tends to be more strongly correlated with VRQoL[13–25], visual field loss in the worse eye is also correlated with VRQoL[15,25], and the difference in explained variance between the two eyes is typically small (i.e., $\Delta R^2 \approx 0.1$[13]). Furthermore, some studies have failed to replicate even this small difference[26] (see also ref~[[27]]). Taken as a whole, these results suggest that peripheral vision is *not* solely a function of the better seeing eye alone, and that the worse eye may also contribute important information. However, it is difficult to draw any firm conclusions from patient self-reports. These studies are not typically intended to examine subtle variations in binocular summation, which may be masked by the intrinsic measurement error of patient self-reports[28]. Furthermore, vision loss in the better and worse eye is often correlated[29,30]. Correlations with VRQoL alone also provide only limited insights regarding effect size: how much harder is it, for example, to “find something on a crowded shelf” as vision in the worse eye varies?

1.2. Present Study

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

2. METHODS

2.1. Task Overview

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

2.2. Participants

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

2.3. Hardware

Stimuli were displayed on a FOVE0 Eye-Tracking VR headset (FOVE Inc., San Mateo, CA, United States). This contains a 2560 X 1440 WQHD OLED panel (1280 x 1440 pixels per eye), with a refresh rate of 70Hz and a binocular field of view of approximately 100 degrees. The headset contained two integrated near-infrared eye-trackers (1 per eye) for independently monitoring gaze in each eye, with a single-frame precision of approximately 1 deg, and a refresh rate of 120 Hz. The headset also contained inertial sensors (gyroscope, accelerometer) for monitoring head-pose. There was no crosstalk[31] between the two eyes, as stimuli --- and simulated impairments --- were presented dichoptically. The software was controlled by a HP OMEN laptop (Hewlett-Packard Company, Palo Alto, CA, United States) containing a NVIDIA GTX 1050Ti graphics card (NVIDIA Corp, Santa Clara, CA, United States).

2.4. Stimuli

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

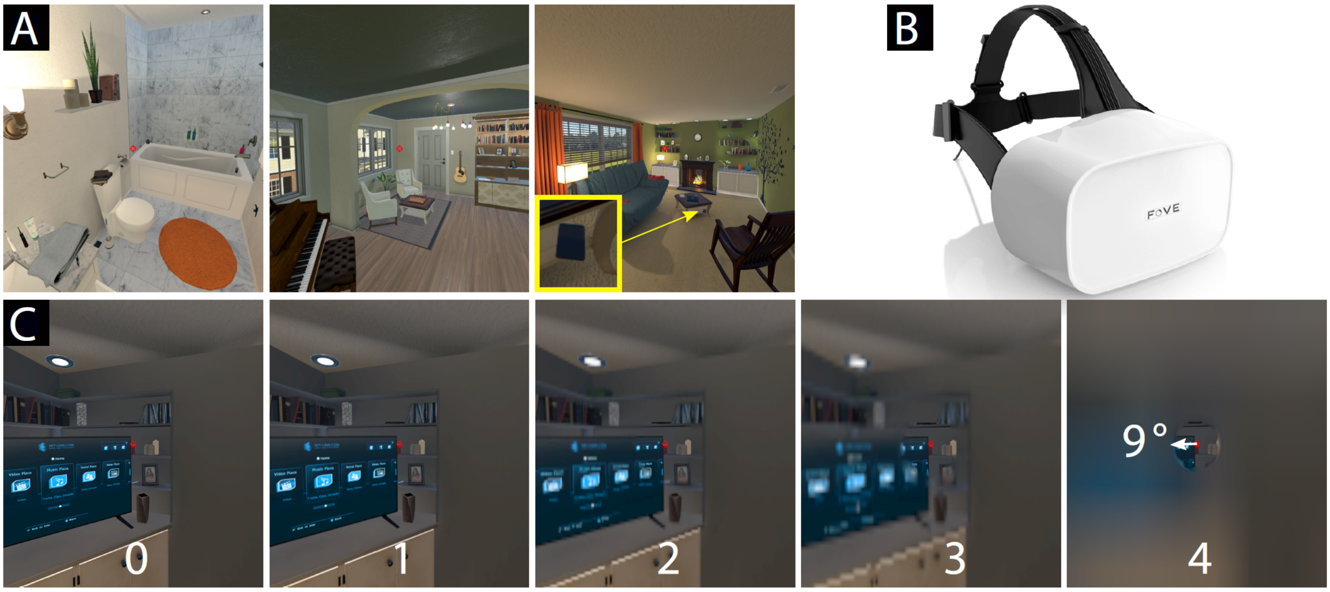

Fig 1: Stimuli and Apparatus. (*A*) Examples of the 15 search environments, and the target (yellow square). See the Supplemental Material for a video depicting additional scenes. (*B*) The FOVE0 head-mounted display, containing independent screens for each eye, and near-infrared eye-tracking. (*C*) The five simulated impairment levels (Level 0 = no blur). The Macula was always spared, by constraining the simulated impairment such that no blur was ever applied to a circular region of radius ±9° (white arrow), centered on the current gaze location (red crosshairs: shown here for illustration only). Note that the observer's gaze was unconstrained (free viewing), and was tracked in near-real-time using the headset's near-infrared sensor.

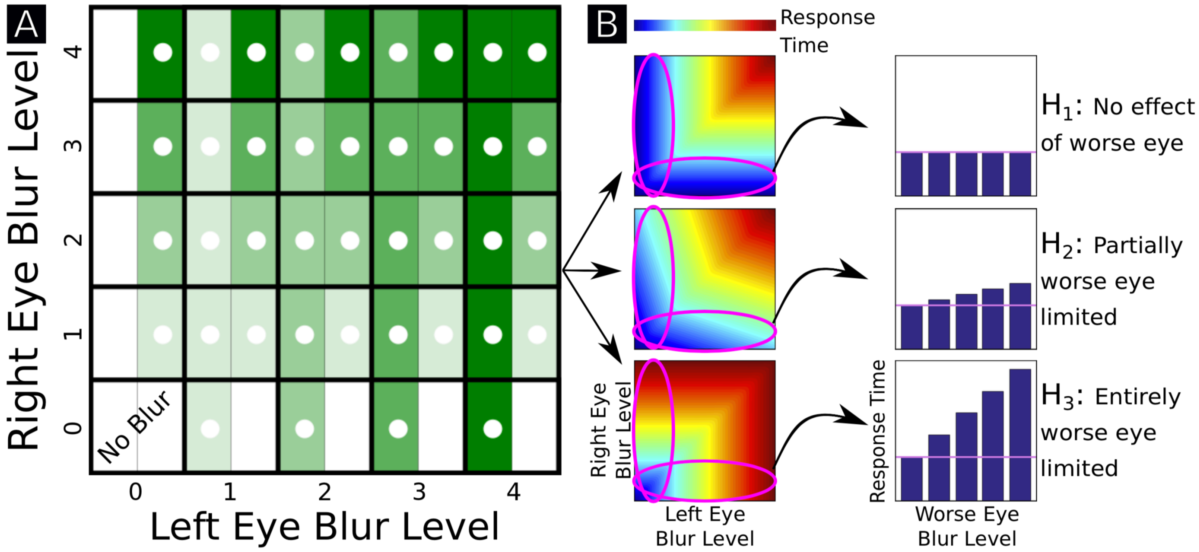

Fig 2: Experimental conditions and hypotheses. (A) A 5 x 5 matrix showing the 25 possible combinations of peripheral vision loss. The intensity of the green shaded regions indicates the magnitude of peripheral loss (blur) in each eye (see Fig 1 for graphical illustrations of each blur level). (B) Three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

2.5. Simulating vision loss

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

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

Blurring was performed in near-real-time using a custom OpenGL fragment shader, which we have made freely available online as part of a general-purpose 'sight loss simulator' toolbox <*methods manuscript under review, TO BE UPDATED*>. In short, prior to each screen refresh, a 'pyramid' of progressively more blurred images was created by a repeated process of decimation (box-filtering and downsampling the source image by a power of two). When drawing the image to the screen, pixels were sampled either from the original source image (regions of no blur), and/or were upsampled from this pyramid of decimated images (regions of blur), using trilinear texture filtering to interpolate between pyramid levels as required. This process is generally referred to as mipmapping, and has been detailed previously in the context of simulating visual field loss by Perry and Geisler[32] (for further technical specifics on the present implementation, see also Ref~[[33]]). The key advantage of this method is its computational efficiency, allowing the screen-location of the gaze-contingent blur to be updated with minimal delay (before every screen refresh).

The type of blur created by this process is qualitatively similar to a gaussian low-pass filter and would not, for example, have completely removed all higher frequency information. Note also, that this approach is intended primarily as a crude model of retinal loss, such as glaucoma, and was applied as a 'post-processing' effect to the final rasterized image. If attempting to simulate vision loss due to optical defocus, it would also be important to incorporate phase-reversals[34,35], and to take into account the distance of each object in the visual scene. The present approach also assumes that observers had negligible refractive error in their periphery, which might otherwise mask the effects of the blur[36]. This was thought reasonable as a first approximation for our cohort of young, normally-sighted adults. However, even young adults with no foveal refractive error can display large degrees of peripheral astigmatism, with substantial variability between observers[37]. This assumption may therefore have introduced a degree of noise (or bias) into the present results: error which could be corrected for in future by adjusting analyses to take into account the unique optical characteristics of each observer.

Note that blur (low-pass filtering) provided a convenient way to parametrically manipulate the level of vision loss in each eye, and is grossly concordant with the self-reports of glaucoma patients with moderate or advanced field loss: who often describe their vision loss in terms of regions of 'blurry' vision[38]. The use of blur was not intended as a comprehensive simulation of real glaucoma, however. Visual impairments are highly heterogeneous, and often involve other symptoms, including metamorphopsia, a loss of lower frequency contrast, and regions of the field becoming jumbled, missing, or elided[39]. Likewise, note that the shape of the visual impairment (an extreme 'tunnel vision' effect) meant that all regions of peripheral vision were degraded. This is not representative of real glaucoma, which is often irregular and includes regions of spared vision. In future, it may be instructive to explore how covarying the shape of the visual field loss also affects performance. However, this was outside of the scope of the present work.

2.6. Test Conditions

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

2.7. Procedure

Participants were instructed to "find the phone as quickly as possible". On each trial, one of fifteen rooms was randomly selected, and the target was randomly placed at one of twenty locations within the room: predefined separately for each room. The location and starting orientation of the participant was also randomized, constrained so that the participant was never directly facing the target at trial onset.

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

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

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

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

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

2.8. Statistical Analysis

The primary question was whether performance varied as vision loss in the worse eye increased (i.e., after adjusting for individual variability, and for the level of vision in the better eye). To test this statistically, data were entered into a Linear Mixed-Effects [LME] model, specified, in Wilkinson (LME) notation[40], as:

$$y \sim 1 + \textsc{WorseEye} + \textsc{BetterEye} + (1 \mid \textsc{PartID}) , \qquad \text{(Eq 1a)}$$

where *WorseEye* was the level of visual impairment (blur) in the worse eye (0 – 100%), *BetterEye* was the level of visual impairment in the better eye (0 – 100%), and *PartID* was the participant ID (1 – 12). The dependent variable, *y*, was computed for each trial, and variously took the form: (i) log_{10} *Response Time*, in seconds; (ii) log_{10} *Total Scan-path Length*, in degrees visual angle; (iii) log_{10} *Total Head-turn Length*, in degrees; and (iv) *answer correct* (0 or 1). A significant main effect of *WorseEye* would mean that a given outcome measure, *y*, varied as peripheral blur in the worse eye increased.

In practice, the LME model in Eq (1a) was fitted by the Matlab function “fitlme” (maximum likelihood method), and the significance of *WorseEye* predictor variable was formally evaluated using Simulated Likelihood Ratio Tests[41]. Note also that this same model can also be specified in standard mathematical notation as:

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

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

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

3. RESULTS

3.1. Response Time

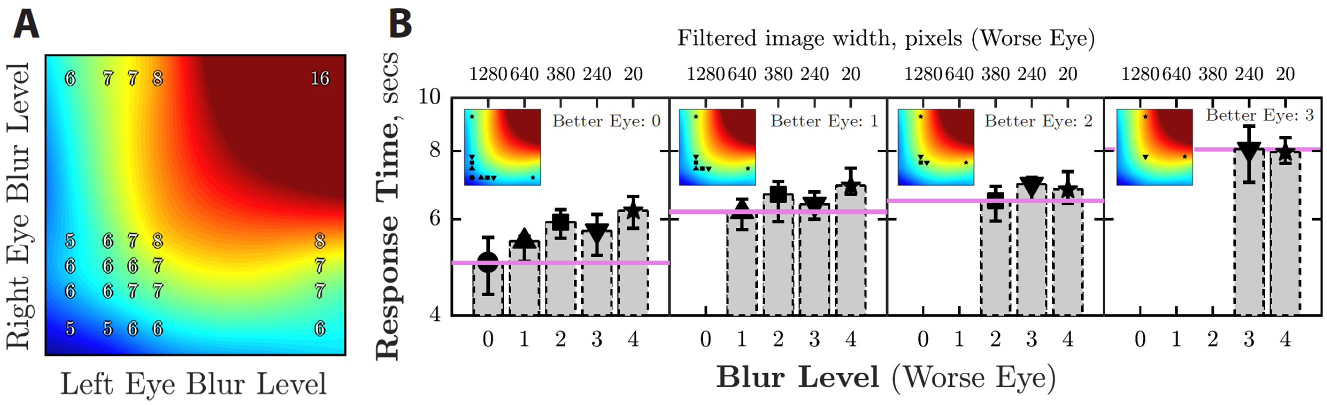

Fig 3. Response time: median time taken to locate the target on each trial, in seconds. ***(A)*** Heatmap showing median response time for each condition (see Fig 2A for details regarding conditions). ***(B)*** Median response time [± 1 S.E.M.], as a function of peripheral loss in the worse eye. Each panel shows a different level of vision loss in the better eye. Each bar shows a different level of vision 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 example, the black square in the first panel is the average response time when peripheral blur in the better eye was Level 0 (no 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 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 line.

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

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

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

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

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

3.2. Eye- and Head-Movements

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

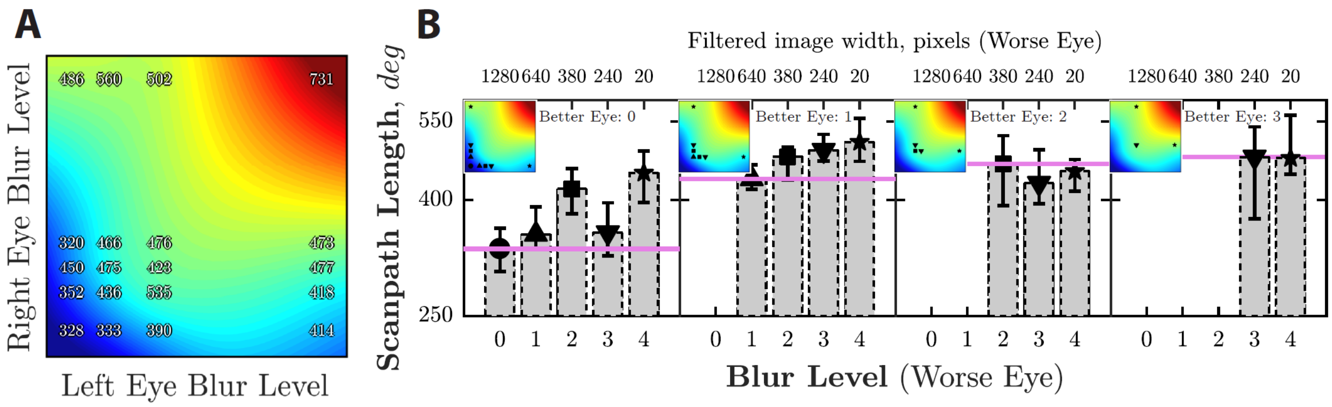

Fig 4. Median scanpath length (amount of eye-movements) on each trial, in degrees. Same format as Figure 3.

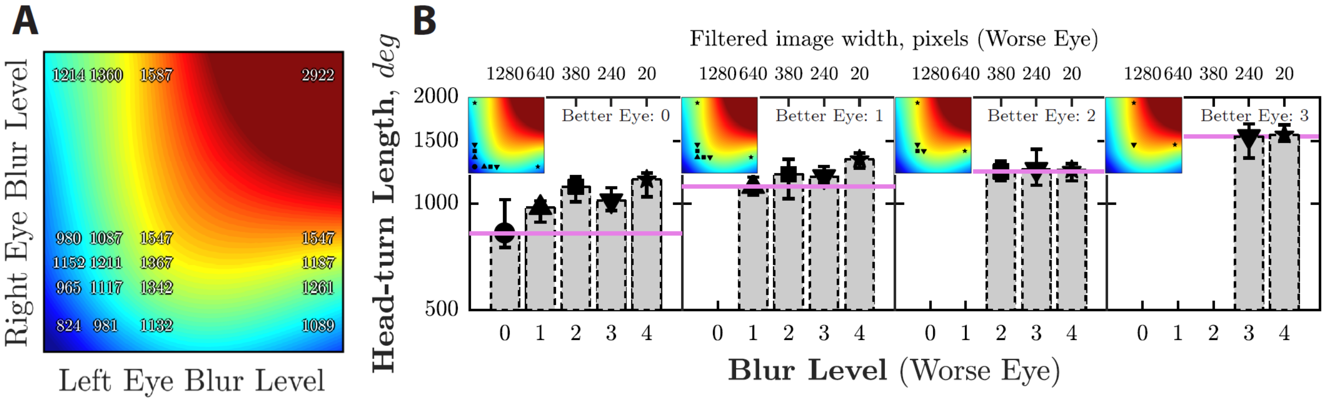

Fig 5. Median head-turn length (amount of head-movements) on each trial, in degrees. Same format as Figure 3.

3.3. Response Accuracy

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

4. DISCUSSION

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

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

4.1. Comparison with Previous Literature

The present data stand in contrast to previous findings using more basic psychophysical tasks (static threshold perimetry), on which binocular sensitivity in the periphery is largely predicted by the better eye alone[2,3]. This mismatch highlights that basic psychophysical tasks do not always provide a perfect model of an individual's ability to perform 'real world' perceptual judgments: a fact which has also been widely reported previously, particularly in the context of visual acuity[6–8] and visual field loss[42–44]. The present findings are, however, broadly consistent with qualitative clinical data. For example, several studies have reported reductions in visual disability and symptoms following second-eye cataract surgery, despite often minimal changes in acuity[45,46]. One corollary of this is that we may in future need to move away from purely 'synthetic' stimuli, such as light-spots, gratings, or isolated optotypes, if we wish to fully characterize the functional impact of sight loss.

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

4.2. Limitations

The present study employed simulated impairments, rather than real patients. This was necessary, as it allowed us to systematically manipulate the impairment and to control for individual differences. It does, however, mean that we have to interpret the results with caution. To the extent that real eye-disease may cause not just high frequency loss (blur), but also a range of other disturbances (low frequency loss, spatial distortions, chromatic anomalies, crowding, infilling, etc.), the worse eye may play an even greater or smaller role than was observed here. Notably, the simulator used in the present study is also capable of incorporating many of these other effects, and these effects can be linked to empirical data from real patients[33]. It would therefore be possible in future to conduct a more comprehensive assessment of how different forms of vision loss affect everyday visually-guided actions, or a detailed analysis of how a particular individual’s visual profile affects daily living. These would be non-trivial undertakings, but the code for the present simulations has been made freely available online for anybody interested in pursuing this line of inquiry <*methods manuscript under review, TO BE UPDATED*>. It likewise remains an open question whether performance would change over time as the individual learns to adapt to their impairment – a consideration which may be particularly relevant to diseases such as glaucoma, where sight loss is often gradual and progressive. The question of adaptation could be explored in future empirically

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

The present data demonstrated that peripheral sight loss affects binocular performance on everyday visual-guided tasks, even when the loss is unilateral. However, they do not tell us how or by what means the worse eye contributes task-relevant information. One possibility is that the change in performance was due primarily to an overall loss of (contrast) sensitivity. Normal vision is comprised of a central binocular field, and two uniocular flankers[50]. By adding blur to the periphery of one eye, the binocular field is shrunken/decreased, limiting opportunities for binocular summation, while one of the flanking regions is lost altogether, effectively narrowing the total field of view. The result is a narrower, shorter 'hill of vision'. In addition to overall changes in sensitivity, however, disrupting binocular vision through the addition of monocular blur can also have secondary consequences, including aberrant motion processing[51] and a loss of (high-frequency) stereopsis[52]. The latter is particularly significant for the present task (Visual Search), since stereopsis is known to be important for `breaking camouflage'[53], while the former may have similar consequences by removing another important depth cue: motion parallax. From the present study, it is not possible to determine which, if any, of these factors are important for explaining the pattern of results observed. In future, however, such questions could be explored experimentally by modifying the present paradigm. For example, instead of applying blur one could selectively remove binocular disparity from the periphery of both eyes. Alternatively, participants could view a 2D plane instead of a 3D environment, to further remove motion parallax cues. To the extent that the same pattern of results continued to hold, it would indicate that it is these secondary depth cues, rather than a loss of sensitivity, that are primarily responsible for changes in performance observed.

A further limitation of the present study is that the central macula region of ± 9° was always spared. We are therefore unable to infer what the effect of unilateral loss would be if this ‘healthy’ region were reduced. The benefits of binocular summation in central vision are, however, well-established, with previous studies showing that observers are better at detecting faint objects[54], resolving fine spatial detail[55,56], or performing delicate visuomotor actions[57], when fixating with two foveae versus just one. We therefore predict that the preservation of the fellow-eye would be at least as beneficial in instances of central or paracentral vision loss. Consistent with this, the same qualitative pattern of results as reported here was observed in a small cohort of observers when the blur was applied uniformly across the whole visual field (see *Supplemental Material D*).

4.3. Implications & Future Work

The present study indicates that there may be a real-world cost to unilateral peripheral vision loss that is not captured by traditional psychophysical measures, such as static threshold perimetry. Such deficits could have particular implications for time-critical tasks, such as driving. Thus, if we consider the conditions involving a purely unilateral impairment (the leftmost panel of Figures 3–5B): such individuals would be expected to score near-perfectly on a standard binocular visual field assessment[2,3,10]. They would therefore be considered legally fit to drive in most countries, even professionally[58]. In contrast, such individuals were 1 second (25%) slower, on average, to locate the target object (and on some trials much slower). To put this in context, when driving at ~30 mph (~50 km/h), an additional 1 second delay in braking is enough to increase stopping distance by 40%[59], and double the likelihood of severely injuring a pedestrian three car-lengths in front[60]. This is particularly concerning given that individuals with unilateral glaucoma are no more likely than their normally-sighted peers to cease driving[61]. At present, we can of course only speculate precisely how the present results would translate to other real-world scenarios, such as driving. It may be, for example, that some drivers can compensate for their vision loss through increased vigilance[62] (though see ref~[[63]]). Notably, the technologies developed for the present work are compatible with all modern software and hardware devices. It would therefore be possible to apply the same simulated impairments to existing driving simulators, and to observe empirically their effects on performance.

More generally, the present work highlights the importance of measuring not only response accuracy, but also response speed and effort, when characterizing a visual impairment. Thus, compared to healthy vision, even an intense, bilateral simulated impairment caused no significant change in response accuracy, which was close to 100% throughout. It did, however, cause response times to be significantly slower (by over 200%, in the bilateral-symmetric case), and compelled participants to make substantially more head- and eye-movements. These findings echo a recent report by Barsingerhorn and colleagues[64], who observed that children with ocular dysfunction were slower at performing a simple spatial judgment (landolt-C orientation-identification) than their normal-sighted peers, even after the stimuli were matched in size for relative acuity. Taken together, such findings suggest that when characterizing vision loss, it may be prudent to move beyond simple functional measures of accuracy. It may, for example, be desirable to consider a treatment effective if it makes visual judgments faster or less tiring, even if there is no substantive change in the size or contrast of the smallest identifiable object. It is interesting to note that this is already an established principle in the auditory community, where fatigue, effort and stress are considered when evaluating hearing impairment[65]. Such constructs are difficult to quantify using traditional 'pen and paper' vision tests, but can be more easily probed using the sorts of digital technologies reported here.

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

4.4. Summary and Conclusions

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

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REFERENCES [*NB: minor/typographic errors will be corrected in the final proof*]

1. Asfaw DS, Jones PR, Mönter VM, Smith ND, Crabb DP. Does Glaucoma Alter Eye Movements When Viewing Images of Natural Scenes? A Between-Eye Study. *Invest Ophthalmol Vis Sci*. 2018;59(8):3189-3198. doi:10.1167/iovs.18-23779

2. Nelson-Quigg JM, Cello K, Johnson CA. Predicting Binocular Visual Field Sensitivity from Monocular Visual Field Results. *Invest Ophthalmol Vis Sci*. 2000;41(8):2212-2221.

3. Wood JM, Collins MJ, Carkeet A. Regional variations in binocular summation across the visual field. *Ophthalmic and Physiological Optics*. 1992;12(1):46-51. doi:10.1111/j.1475-1313.1992.tb00253.x

4. Crabb DP, Viswanathan AC. Integrated visual fields: a new approach to measuring the binocular field of view and visual disability. *Graefe's Archive for Clinical and Experimental Ophthalmology*. 2005;243(3):210-216. doi:10.1007/s00417-004-0984-x

5. Musch DC, Niziol LM, Gillespie BW, Lichter PR, Janz NK. Binocular Measures of Visual Acuity and Visual Field versus Binocular Approximations. *Ophthalmology*. 2017;124(7):1031-1038. doi:10.1016/j.ophtha.2017.02.013

6. Rubin GS, Muñoz B, Bandeen–Roche K, West SK. Monocular versus Binocular Visual Acuity as Measures of Vision Impairment and Predictors of Visual Disability. *Invest Ophthalmol Vis Sci*. 2000;41(11):3327-3334.

7. Brabyn J, Schneck M, Haegerstrom-Portnoy G, Lott L. The Smith-Kettlewell Institute (SKI) longitudinal study of vision function and its impact among the elderly: an overview. *Optom Vis Sci*. 2001;78(5):264-269. doi:10.1097/00006324-200105000-00008

8. Rahi JS, Cumberland PM, Peckham CS. Visual Impairment and Vision-Related Quality of Life in Working-Age Adults: Findings in the 1958 British Birth Cohort. *Ophthalmology*. 2009;116(2):270-274. doi:10.1016/j.ophtha.2008.09.018

9. Jones PR. A tutorial on cue combination and Signal Detection Theory: Using changes in sensitivity to evaluate how observers integrate sensory information. *Journal of Mathematical Psychology*. 2016;73:117-139. doi:10.1016/j.jmp.2016.04.006

10. Graham CH. An Investigation of Binocular Summation: II. The Periphery: The Journal of General Psychology: Vol 5, No 3. *The Journal of General Psychology*. 1931;5(3):311.

11. Zlatkova MB, Anderson RS, Ennis FA. Binocular summation for grating detection and resolution in foveal and peripheral vision. *Vision Research*. 2001;41(24):3093-3100. doi:10.1016/S0042-6989(01)00191-2

12. Mangione CM, Lee PP, Gutierrez PR, Spritzer K, Berry S, Hays RD. Development of the 25-list-item National Eye Institute Visual Function Questionnaire. *Arch Ophthalmol*. 2001;119(7):1050-1058. doi:10.1001/archopht.119.7.1050

13. van Gestel A, Webers CAB, Beckers HJM, et al. The relationship between visual field loss in glaucoma and health-related quality-of-life. *Eye*. 2010;24(12):1759-1769. doi:10.1038/eye.2010.133

14. Hirneiss C. The impact of a better-seeing eye and a worse-seeing eye on vision-related quality of life. *Clin Ophthalmol*. 2014;8:1703-1709. doi:10.2147/OPTH.S64200

15. Hyman LG, Komaroff E, Heijl A, Bengtsson B, Leske MC. Treatment and Vision-Related Quality of Life in the Early Manifest Glaucoma Trial. *Ophthalmology*. 2005;112(9):1505-1513. doi:10.1016/j.ophtha.2005.03.028

16. Janz NK, Wren PA, Lichter PR, Musch DC, Gillespie BW, Guire KE. Quality of life in newly diagnosed glaucoma patients. *Ophthalmology*. 2001;108(5):887-897. doi:10.1016/S0161-6420(00)00624-2

17. Kulkarni KM, Mayer JR, Lorenzana LL, Myers JS, Spaeth GL. Visual Field Staging Systems in Glaucoma and the Activities of Daily Living. *American Journal of Ophthalmology*. 2012;154(3):445-451.e3. doi:10.1016/j.ajo.2012.03.030

18. McKean-Cowdin R, Varma R, Wu J, Hays RD, Azen SP. Severity of Visual Field Loss and Health-related Quality of Life. *American Journal of Ophthalmology*. 2007;143(6):1013-1023. doi:10.1016/j.ajo.2007.02.022

19. McKean-Cowdin R, Wang Y, Wu J, Azen SP, Varma R. Impact of Visual Field Loss on Health-Related Quality of Life in Glaucoma. *Ophthalmology*. 2008;115(6):941-948.e1. doi:10.1016/j.ophtha.2007.08.037

20. Okamoto M, Sugisaki K, Murata H, Hirasawa H, Mayama C, Asaoka R. Impact of better and worse eye damage on quality of life in advanced glaucoma. *Scientific Reports*. 2015;4(1). doi:10.1038/srep04144

21. Peters D, Heijl A, Brenner L, Bengtsson B. Visual impairment and vision-related quality of life in the Early Manifest Glaucoma Trial after 20 years of follow-up. *Acta Ophthalmologica*. 2015;93(8):745-752. doi:10.1111/aos.12839

22. Sawada H, Yoshino T, Fukuchi T, Abe H. Assessment of the Vision-specific Quality of Life Using Clustered Visual Field in Glaucoma Patients: *Journal of Glaucoma*. 2014;23(2):81-87. doi:10.1097/IJG.0b013e318265bbdc

23. Sumi I, Shirato S, Matsumoto S, Araie M. The Relationship between Visual Disability and Visual Field in Patients with Glaucoma. 2003;110(2):8.

24. Sun MJ, Rubin GS, Akpek EK, Ramulu PY. Impact of Glaucoma and Dry Eye on Text-Based Searching. *Trans Vis Sci Tech*. 2017;6(3):24-24. doi:10.1167/tvst.6.3.24

25. Murata H, Hirasawa H, Aoyama Y, et al. Identifying Areas of the Visual Field Important for Quality of Life in Patients with Glaucoma. *PLOS ONE*. 2013;8(3):e58695. doi:10.1371/journal.pone.0058695

26. Khadka J, Pesudovs K, McAlinden C, Vogel M, Kernt M, Hirneiss C. Reengineering the Glaucoma Quality of Life-15 Questionnaire with Rasch Analysis. *Invest Ophthalmol Vis Sci*. 2011;52(9):6971-6977. doi:10.1167/iovs.11-7423

27. Haymes SA, LeBlanc RP, Nicolela MT, Chiasson LA, Chauhan BC. Glaucoma and On-Road Driving Performance. *Investigative Opthalmology & Visual Science*. 2008;49(7):3035. doi:10.1167/iovs.07-1609

28. Jones L, Garway-Heath DF, Azuara-Blanco A, et al. Are Patient Self-Reported Outcome Measures Sensitive Enough to Be Used as End Points in Clinical Trials? *Ophthalmology*. September 2018. doi:10.1016/j.ophtha.2018.09.034

29. Arora KS, Boland MV, Friedman DS, Jefferys JL, West SK, Ramulu PY. The Relationship between Better-Eye and Integrated Visual Field Mean Deviation and Visual Disability. *Ophthalmology*. 2013;120(12):2476-2484. doi:10.1016/j.ophtha.2013.07.020

30. Choi JA, Jung I-Y, Jee D. The Relationship Between the Sighting Eye and Functional and Structural Asymmetries in Glaucoma. *Invest Ophthalmol Vis Sci*. 2018;59(13):5447-5454. doi:10.1167/iovs.18-24083

31. Baker DH, Kaestner M, Gouws AD. Measurement of crosstalk in stereoscopic display systems used for vision research. *Journal of Vision*. 2016;16(15):14-14. doi:10.1167/16.15.14

32. Geisler WS, Perry G. Real-time Simulation of Arbitrary Visual Fields. *Proceedings of the 2002 symposium on eye tracking research & applications*. 2002:83-87.

33. Jones PR, Ometto G. Degraded Reality: Using VR/AR to simulate visual impairments. In: *2018 IEEE Workshop on Augmented and Virtual Realities for Good (VAR4Good)*. ; 2018:1-4. doi:10.1109/VAR4GOOD.2018.8576885

34. O’Hare L, Hibbard PB. Visual discomfort and blur. *Journal of Vision*. 2013;13(5):7-7. doi:10.1167/13.5.7

35. Murray S, Bex PJ. Perceived Blur in Naturally Contoured Images Depends on Phase. *Frontiers in Psychology*. 2010;1. doi:10.3389/fpsyg.2010.00185

36. Anderson RS, McDowell DR, Ennis FA. Effect of localized defocus on detection thresholds for different sized targets in the fovea and periphery. *Acta Ophthalmologica Scandinavica*. 2001;79(1):60-63. doi:10.1034/j.1600-0420.2001.079001060.x

37. Gustafsson J, Terenius E, Buchheister J, Unsbo P. Peripheral astigmatism in emmetropic eyes. *Ophthalmic and Physiological Optics*. 2001;21(5):393-400. doi:10.1046/j.1475-1313.2001.00606.x

38. Crabb DP, Smith ND, Glen FC, Burton R, Garway-Heath DF. How does glaucoma look?: patient perception of visual field loss. *Ophthalmology*. 2013;120(6):1120-1126.

39. Hu CX, Zangalli C, Hsieh M, et al. What Do Patients With Glaucoma See? Visual Symptoms Reported by Patients With Glaucoma. *Am J Med Sci*. 2014;348(5):403-409. doi:10.1097/MAJ.0000000000000319

40. Wilkinson GN, Rogers CE. Symbolic description of factorial models for analysis of variance. *J Royal Statistics Society*. 1973:392-399.

41. Stram DO, Lee JW. Variance Components Testing in the Longitudinal Mixed Effects Model. *Biometrics*. 1994;50(4):1171. doi:10.2307/2533455

42. Abe RY, Diniz-Filho A, Costa VP, Gracitelli CPB, Baig S, Medeiros FA. The Impact of Location of Progressive Visual Field Loss on Longitudinal Changes in Quality of Life of Patients with Glaucoma. *Ophthalmology*. 2016;123(3):552-557. doi:10.1016/j.ophtha.2015.10.046

43. Chun YS, Sung KR, Park CK, et al. Vision-related quality of life according to location of visual field loss in patients with glaucoma. *Acta Ophthalmologica*. 0(0). doi:10.1111/aos.14020

44. Cheng H-C, Guo C-Y, Chen M-J, Ko Y-C, Huang N, Liu CJ. Patient-Reported Vision-Related Quality of Life Differences Between Superior and Inferior Hemifield Visual Field Defects in Primary Open-Angle Glaucoma. *JAMA Ophthalmology*. 2015;133(3):269. doi:10.1001/jamaophthalmol.2014.4908

45. Elliott DB, Patla A, Bullimore MA. Improvements in clinical and functional vision and perceived visual disability after first and second eye cataract surgery. *British Journal of Ophthalmology*. 1997;81(10):889-895. doi:10.1136/bjo.81.10.889

46. Laidlaw A, Harrad R. Can second eye cataract extraction be justified? *Eye*. 1993;7(5):680-686. doi:10.1038/eye.1993.155

47. Smith ND, Glen FC, Crabb DP. Eye movements during visual search in patients with glaucoma. *BMC Ophthalmology*. 2012;12(1). doi:10.1186/1471-2415-12-45

48. Lee SS-Y, Black AA, Wood JM. Effect of glaucoma on eye movement patterns and laboratory-based hazard detection ability. *PLOS ONE*. 2017;12(6):e0178876. doi:10.1371/journal.pone.0178876

49. Dive S, Rouland JF, Lenoble Q, Szaffarczyk S, McKendrick AM, Boucart M. Impact of Peripheral Field Loss on the Execution of Natural Actions: A Study With Glaucomatous Patients and Normally Sighted People. *Journal of Glaucoma*. 2016;25(10):e889-e896. doi:10.1097/IJG.0000000000000402

50. Henson DB. *Visual Fields*. Oxford; New York: Oxford University Press; 1993.

51. Burge J, Rodriguez-Lopez V, Dorronsoro C. Monovision and the Misperception of Motion. *Current Biology*. 2019;29(15):2586-2592.e4. doi:10.1016/j.cub.2019.06.070

52. Li RW, So K, Wu TH, et al. Monocular blur alters the tuning characteristics of stereopsis for spatial frequency and size. *R Soc Open Sci*. 2016;3(9). doi:10.1098/rsos.160273

53. Bela julesz. Foundations of cyclopean perception. Chicago: University of chicago press, 1971 - Yellott - 1972 - Behavioral Science - Wiley Online Library. https://onlinelibrary.wiley.com/doi/pdf/10.1002/bs.3830170307. Accessed August 20, 2019.

54. Blake R, Fox R. The psychophysical inquiry into binocular summation. *Perception & Psychophysics*. 1973;14(1):161-185. doi:10.3758/BF03198631

55. Heravian JS, Jenkins TCA, Douthwaite WA. Binocular summation in visually evoked responses and visual acuity. *Ophthalmic and Physiological Optics*. 1990;10(3):257-261. doi:10.1111/j.1475-1313.1990.tb00861.x

56. Horowitz MW. An analysis of the superiority of binocular over monocular visual acuity. *Journal of Experimental Psychology*. 1949;39(5):581-596. doi:10.1037/h0056892

57. Read JCA, Begum SF, McDonald A, Trowbridge J. The Binocular Advantage in Visuomotor Tasks Involving Tools. *i-Perception*. 2013;4(2):101-110. doi:10.1068/i0565

58. Kotecha A, Spratt A, Viswanathan A. Visual function and fitness to drive. *British Medical Bulletin*. 2008;87(1):163-174. doi:10.1093/bmb/ldn028

59. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets.* Washington: AASHTO; 2011.

60. Tefft BC. Impact speed and a pedestrian's risk of severe injury or death. *Accident Analysis & Prevention*. 2013;50:871-878. doi:10.1016/j.aap.2012.07.022

61. Ramulu PY, West SK, Munoz B, Jampel HD, Friedman DS. Driving Cessation and Driving Limitation in GlaucomaThe Salisbury Eye Evaluation Project. *Ophthalmology*. 2009;116(10):1846-1853. doi:10.1016/j.ophtha.2009.03.033

62. Kübler TC, Kasneci E, Rosenstiel W, et al. Driving with Glaucoma: Task Performance and Gaze Movements. *Optometry and Vision Science*. 2015;92(11):1037. doi:10.1097/OPX.0000000000000702

63. Prado Vega R, van Leeuwen PM, Rendón Vélez E, Lemij HG, de Winter JCF. Obstacle Avoidance, Visual Detection Performance, and Eye-Scanning Behavior of Glaucoma Patients in a Driving Simulator: A Preliminary Study. *PLoS One*. 2013;8(10). doi:10.1371/journal.pone.0077294

64. Barsingerhorn AD, Boonstra FN, Goossens J. Symbol Discrimination Speed in Children With Visual Impairments. *Invest Ophthalmol Vis Sci*. 2018;59(10):3963-3972. doi:10.1167/iovs.17-23167

65. Hicks CB, Tharpe AM. Listening effort and fatigue in school-age children with and without hearing loss. *Journal of Speech, Language, and Hearing Research; Rockville*. 2002;45(3):573-584.

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

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

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

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

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

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

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

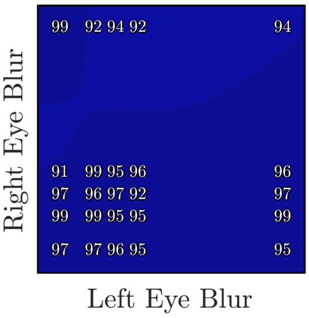

Fig S1. Response accuracy: percent correct responses as a function of left eye impairment level (abscissa) and right eye impairment level (ordinate).

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

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

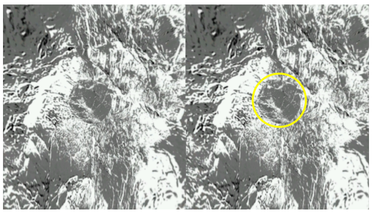

Fig S2. Example stimuli (left-eye/right-eye) for a pilot 'texture search' variant of the main task, in which the target and search environment were replaced with patterns of random noise. Impairments are not shown, but consisted of variable blur similar to that illustrated in Fig 1 of the main manuscript.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

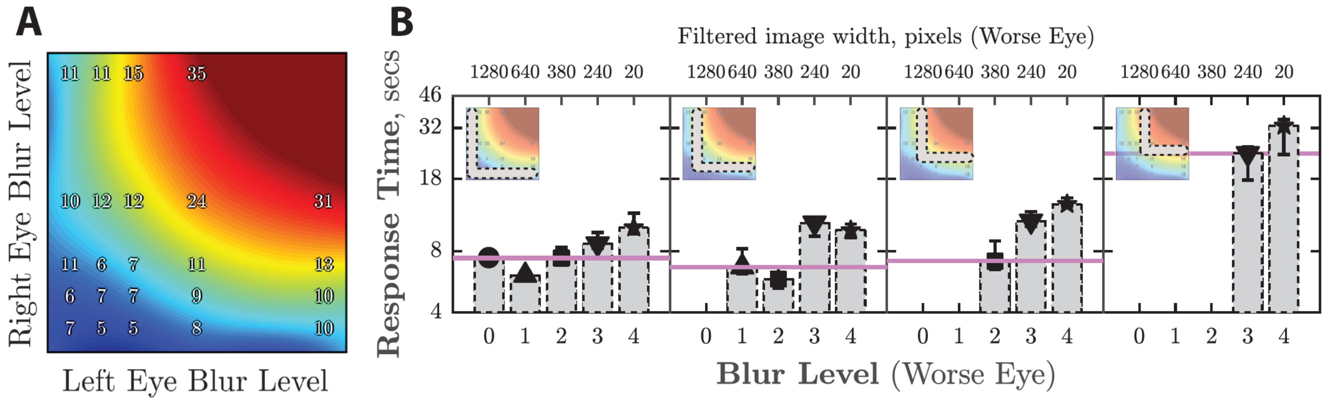

Fig S3. Response time data for a pilot 'texture search' variant of the main task (see Fig S2 for stimuli). These data are analogous to the those shown previously in Figure 3 (main manuscript), and exhibit a similar overall pattern. In this case, however, data are from 5 participants only, and the size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

D. Supplemental Experiment: Uniform blur condition

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

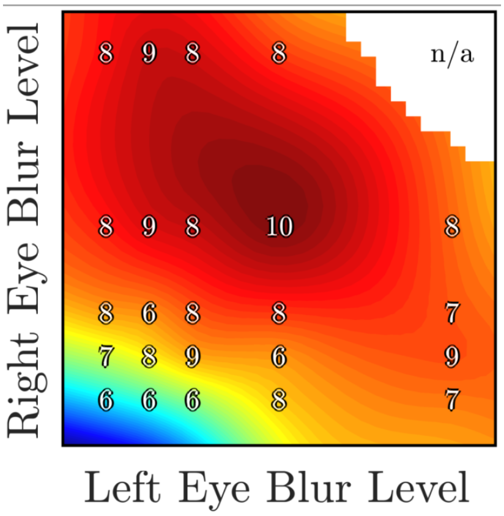

Fig S4. Response time data for a "uniform blur" variant of the main experiment. These data are analogous to the those shown previously in Figure 3A (*Main Manuscript*).