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"Practice-related changes in eye movement strategy in healthy adults with simulated hemianopia"

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Abstract

The impact of visual field deficits such as hemianopia can be mitigated by eye movements that position the visual image within the intact visual field. Effective eye movement strategies are not observed in all patients, however, and it is not known whether persistent deficits are due to injury or to pre-existing individual differences. Here we examined whether repeated exposure to a search task with rewards for good performance would lead to better eye movement strategies in healthy individuals. Participants were exposed to simulated hemianopia during a search task in five testing sessions over five consecutive days and received monetary payment for improvements in search times. With practice, most participants made saccades that went further into the blind field earlier in search, specifically under conditions where little information about the target location would be gained by inspecting the sighted field. These changes in search strategy were correlated with reduced search times. This strategy improvement also generalised to a novel task, with better performance in naming

objects in a photograph under conditions of simulated hemianopia after practice with visual search compared to a control group. However, even after five days, eye movements in most participants remained far from optimal. The results demonstrate the benefits, and limitations, of practice and reward in the development of effective coping strategies for visual field deficits.

Key words:

Visual search, optimality, blindsight, hemianopia

Partial binocular visual field loss such as hemianopia has a profound impact on day-to-day functioning and is often associated with difficulties carrying out daily activities such as reading (Schuett, Heywood, Kentridge, & Zihl, 2008), driving (Papageorgiou, 2007), and navigating in familiar and unfamiliar environments (Han, Law-Gibson, & Reding, 2002; Kerkhoff, 2000; Papageorgiou, Hardiess, Schaeffel, Wiethoelter, Karnath, Mallot, Schoenfisch, & Schiefer, 2007; Zihl, 1995). The adverse effects of hemianopia on the interactions with the environment can be reduced by effective eye movements that strategically position the target visual image within the intact visual field. For example, a patient with left visual field loss could fixate the left edge of busy sidewalk, rather than the center, to avoid colliding with other pedestrians. Some patients spontaneously compensate for their visual field loss over time by adopting more efficient eye movement strategies (Zihl, 1999; Zihl & von Cramon, 1985), but an estimated 60% of patients continue using ineffective scanning strategies when searching for a target object (Zihl, 1995). One technique that has been shown to improve patients' visual exploratory abilities is visual search training, which encourages

patients to make exploratory eye movements into the blind field (Pambakian, Currie & Kennard, 2005; Pambakian, Mannan, Hodgson & Kennard, 2004). In laboratory settings, improvements have been noted after an average of 15 hours of training in 14 previous studies (See Sahraie et al., 2016 for a review) but some improvements after as little as only one session of therapy (300 trials) have also been reported (Jacquin-Courtois, Bays, Salemme, Leff & Husain, 2012). Applying these strategies in real life has been associated with self-reported improvements in general functioning (Mannan, Pambakian & Kennard, 2010; Nelles, Esser, Eckstein, Tiede, Gerhard & Diener, 2001). It is important to note, however, that eccentric fixation strategies come with the cost of lower visual acuity as items of interest are viewed peripherally.

In training studies, participants are typically given specific instructions and are encouraged to use a particular strategy. Is this required, or can an efficient strategy develop spontaneously simply through exposure to the deficit and practice with a search task in the absence of any specific instruction? An influential model of visual search suggests that healthy human observers can use optimal strategies without specific instructions (Najemnik & Geisler, 2005; 2008). In the optimal or ideal search model, eye movements are directed to locations that are expected to lead to the highest possible information gain, and the authors who developed the model found that it matched human search in terms of the number of eye movements it required to find a target. But this model's premise is inconsistent with research revealing profound failures to direct eye movement to locations that could maximise information gain (Clarke & Hunt, 2016; Morvan & Maloney, 2012; Verghese, 2012). The results of these latter studies are more consistent with a stochastic model of eye movements during search, where each eye movement is randomly selected from a population of the eye

movements participants can make from that region of the screen (Clarke, Greene, Chantler & Hunt, 2016; Clarke, Stainer, Tatler & Hunt, 2017).

From related experiments in our lab, we also know that healthy individuals without visual field deficits show large variation in search strategies, with some of them being very efficient searchers, and some using a very inefficient strategy (Nowakowska, Clarke, & Hunt, 2017). Indeed, the large range of individual differences has been documented in numerous behavioural, electrophysiological and even neuroanatomical studies, showing the variations in pattern of connectivity in different individuals. Variability in patients' performance, on the other hand, has often been attributed to factors such as site and extent of the lesion and age at the onset as well as differing retro- and anterograde patterns of degenerations post lesion (see for example Zihl, 1999, Tant, 2002). One detail that is often lacking in patient studies, however, is the knowledge of premorbid performance. Hence, although different lesions result in different deficiencies, the baseline performance levels are also variable. Furthermore, it is also possible that some particular premorbid patterns of connectivity can make some patients more susceptible to develop residual capacities to process some visual stimuli. This has been shown, for example in the unusual pattern of projection to the contra-lesioned MT in a famous blindsight case GY (Bridge, Thomas, Jbabdi, & Cowey, 2008). Our goal in this experiment is to provide baseline information about how individuals adapt their eye movements to compensate for visual information loss like that seen in hemianopia, and to document how their eye movement patterns change under repeated exposure with strong incentives to improve.

We recently investigated the strategies that healthy participants spontaneously adopt to compensate for simulated visual deficit (Nowakowska, Clarke, Sahraie & Hunt,

2016). In that study, visual information in one hemifield was removed or degraded while participants searched for a line tilted 45° to the right among lines of varying degree of tilt in one set of studies, or an angry face among neutral faces in the second set of studies. A rational search strategy would be to look towards the degraded field, and to do so to an increasing extent the more it is degraded. We found the opposite: there was a bias towards the sighted field, and the proportion of saccades directed towards the blind field increased as the simulated deficit became less severe. We also kept the target line tilt constant but varied the background pattern to observe the effect on search strategies. The logic was that when the target is difficult to see against a complex background, it does not matter whether participants search the sighted or blind field first, as they need to serially inspect each location to determine if the target is present or not. If the background is simple, however, and the target is consequently highly visible in the periphery, participants can quickly ascertain from a central point whether or not the target is present or absent in the sighted field, without making any eye movements. Eye movements towards the sighted field will provide little new information and increase search times under these circumstances; indeed, they substantially *decrease* the perceived information by shifting the simulated deficit across a larger proportion of search area. Nonetheless, our participants frequently directed eye movements towards the sighted field even though the target was obviously absent, exhibiting surprisingly inefficient search behaviour.

Our finding that participants fail to adopt efficient strategies to compensate for simulated visual deficits is inconsistent with theories suggesting human search is optimal (Najemnik & Geisler, 2005; 2008). These results also justify the use of specialized training for helping patients learn to cope with visual deficits, as they

suggest patients otherwise persist in using ineffective strategies. However, it is important to note that simulated hemianopia is an unusual circumstance for our healthy participants, and it may not be warranted to conclude that they are sub-optimal at adapting their search after only one session. In the current study we investigate whether repeated exposure to a simulated visual field deficit leads to the development of an efficient search strategy. Participants searched for a line segments under conditions of simulated hemianopia every day for five consecutive days, with financial incentives associated with improvements in performance.

In the first and last session of the five-day experiment, participants completed two additional tasks: detection and object naming. The aim of the detection task was to measure the extent to which improvements in search performance over the five sessions could be due to practice related enhancement in perceptual sensitivity to the target rather than to changes in eye movement strategies. Like the search task, the object naming task was also carried out under simulated hemianopia, and was used to estimate the extent to which any improvements in performance in the repeated exposure task would transfer to other images/tasks. A control group performed just the detection and object naming tasks on the first and last day, without any intervening exposure to the simulated deficit. If we do observe increasingly efficient search over the week, we can measure whether this learning transfers to the object naming task by comparing improvements on the object-naming task between the repeated-exposure and control groups.

Method

Participants. Thirty-four participants (age range = 19-36; mean age = 22.8 ± 3.99) completed the experiment. Seventeen participants were in the repeated exposure group (females = 15) and 17 were in the control group (females = 12). All reported normal or corrected-to-normal vision.

Apparatus. The display was presented on a 17inch CRT monitor with a resolution of 1024x768. Stimulus generation, presentation and data collection were controlled by Matlab and the psychophysics toolbox (Brainard, 1997; Pelli, 1997) run on a Powermac. The position of the dominant eye was recorded using a desktop-mounted EyeLink 1000 eye tracker (SR Research, Canada), sampling eye position at 1000Hz. The duration of the system's delay was 1.5ms (time taken from registering a new sample to sending the command to update the screen).

Overview of Procedure. On arrival at the laboratory each participant was asked to read and sign an information sheet/consent form and was seated alone in a small, low-lit room. In the first and fifth sessions, the repeated exposure group participants did three tasks: an object-naming task, detection task, and a search task, and their eye movements were recorded while performing each of the tasks. On the intervening three days, participants in this group only completed the search task. The control group completed the object-naming and detection tasks during the first and fifth day with no search sessions in the intervening days. The three tasks are described in detail below. Participants were not given any information about hemianopia or simulated hemianopia until they finished the last session. At the end of the first session, the experimenter reminded participants in the repeated exposure group that they would be paid 20 pounds for their participation in the experiment regardless of their performance. At this point, the experimenter also added that they would also receive an

additional £5 for any session in which they improved their reaction times compared to their best performance on any previous session, provided their accuracy stayed at least the same as on the first session. Participants were given this information after completing the first session to ensure they did not deliberately under-perform. Thus participants in the repeated exposure group could be reimbursed a maximum of £40 pounds if their performance improved on every session. Participants in the control group received 10 pounds for completing the two sessions.

Repeated search task

This task was completed by the repeated exposure group for five consecutive days (Monday to Friday). Each participant was tested under two experimental conditions: *Simulated Hemianopia* and *Normal Viewing* (i.e. no mask). Under the simulated hemianopia condition the eye-tracker sampled the current gaze position online and replaced the part of the display falling to the left or right of current fixation (blocked) with the grey background. In the *Normal Viewing* condition eye movements were recorded but no mask was applied. Participants completed three blocks of 80 trials (240 trials total) in each session: one block masked to the left, one to the right, and one block with no mask (Normal Viewing). Block order was counterbalanced in each session. Participants were informed of the condition and underwent a nine-point eye movement calibration sequence before each block of trials.
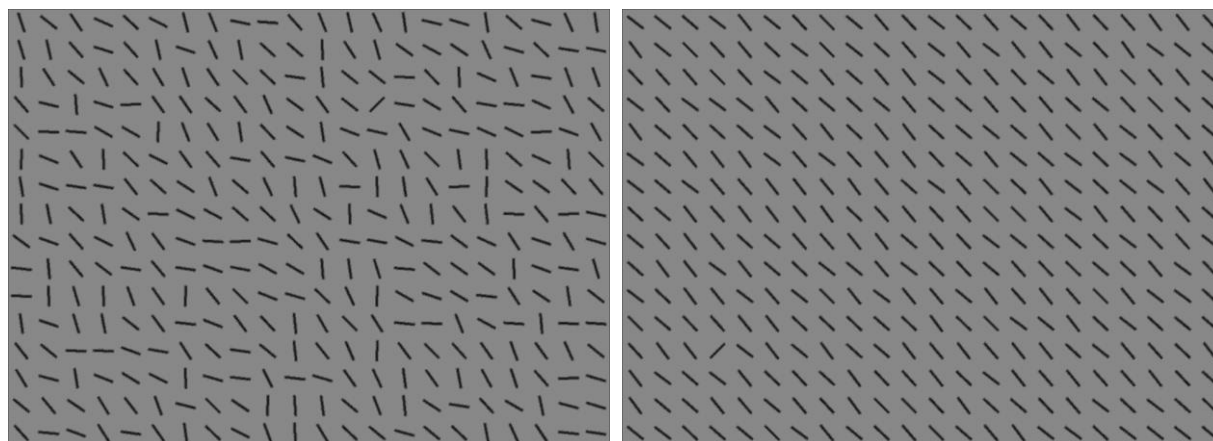
Figure 1. Example line segments: the left panel shows the target (a line tilted 45˚ to the right) on a background of distractor lines with a 95˚ range of variation (hard search), and right panel shows the target on a background of distractor lines with an 18˚ range of variation (easy search).

The stimuli in each block consisted of 80 pre-generated arrays of line segments. Each line was 1.2cm (1.5° at a viewing distance of 45 cm) long. The segments were aligned in 22 columns and 16 rows. The target line was always tilted 45 degrees to the right and the mean distractor angle was perpendicular to the target angle. The target could be located in any of the possible locations apart from the first and last row and column and the middle two rows and columns. Of the 80 images, 40 were target present and 40 target absent. We introduced two levels of search difficulty, with each level corresponding to the distribution from which the distractor line orientation was drawn relative to the target. The distractor angle range of 95° (range of possible distractor angles from the mean orientation) was the high task difficulty condition and the range of 18° was the easy condition (see Figure 1 for example stimuli). These two search conditions will be referred to as "easy" and "hard" respectively. There were forty search arrays of each difficulty level. The target was present 20 times on the left and 20 times on the right hand side of the screen. The lines were located on a uniform grey background. The background and mask luminances were matched (17 ± 1 cd/ m^2).

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Each trial began with a black fixation point (letter x) subtending 1.5x2.5cm (1.9°x3.2°), presented at the centre of the computer screen. On the press of a space bar, the fixation point was replaced by the search array after a 1000ms delay, with the mask applied according to the condition. For example, in the right-side simulated hemianopia block the display was increasingly uncovered as the participants moved their eyes to the far right, and as they moved their eyes to the left the screen was increasingly covered with the mask. The display remained on the screen until the participant made their response, or after 60 seconds had elapsed without a response. The participants were asked to respond by pressing either the left arrow key (for target present trials) or right arrow key (for target absent trials) on a standard keyboard. The display was replaced with the initial fixation point for the next trial 200ms after the left or right arrow key was pressed. The target was present on half of all trials in each block and the participants' task was to indicate the presence or absence of a target. All participants were asked to respond as quickly and as accurately as possible. Auditory feedback in the form of a beep immediately followed every incorrect key press. The position of the dominant eye was recorded using a desktop-mounted EyeLink 1000 eye tracker (SR Research, Canada) sampling eye position at 1000Hz. The length of the eye tracking system's delay was 1.5ms (time taken from registering a new sample to screen update), and the refresh rate 120Hz, so the absolute maximum delay for updating would be 9.5ms. To simulate small macular sparing and not to bisect the current point of fixation, the mask was drawn 1° from central fixation. One participant reported the mask to be "jittery" at one point during the experiment, however this was rectified following EyeLink re-calibration. The mask disappears during the blinks, however the refresh rate is fast enough that this is not an issue in the experiment (in other words, it is impossible to see the stimuli by blinking frequently).

Detection task

In the repeated exposure group, a detection task was carried out before the first repeated search block on Monday and after the last repeated search block on Friday. In the control group, it was the first task carried out on both Monday and Friday. The 80 search arrays of line segments we used in this experiment were exactly the same as the ones in the Repeated Exposure Task. No masks were applied. Participants were told they would see line segments on the screen for a very short time, and their task was to determine whether a line tilted 45° to the right was present among other lines. Participants were asked to respond as accurately as possible and to guess if not sure about the answer.

Each trial consisted of a black fixation point (letter x) subtending 1.5x2.5cm (1.9°x3.2°), presented at the centre of the computer screen. On the press of a space bar, the stimulus was displayed for 200ms follow by a blank screen. Participants had to press either the left (present) or right (absent) arrow key. Auditory feedback in the form of a beep immediately followed incorrect key presses. Before the start of the experiment participants underwent a five-point calibration sequence.

Object Naming task

This task was introduced to investigate if any improvements in eye movement strategies under conditions of simulated hemianopia after repeated exposure to the search task would transfer to other tasks and stimulus types.
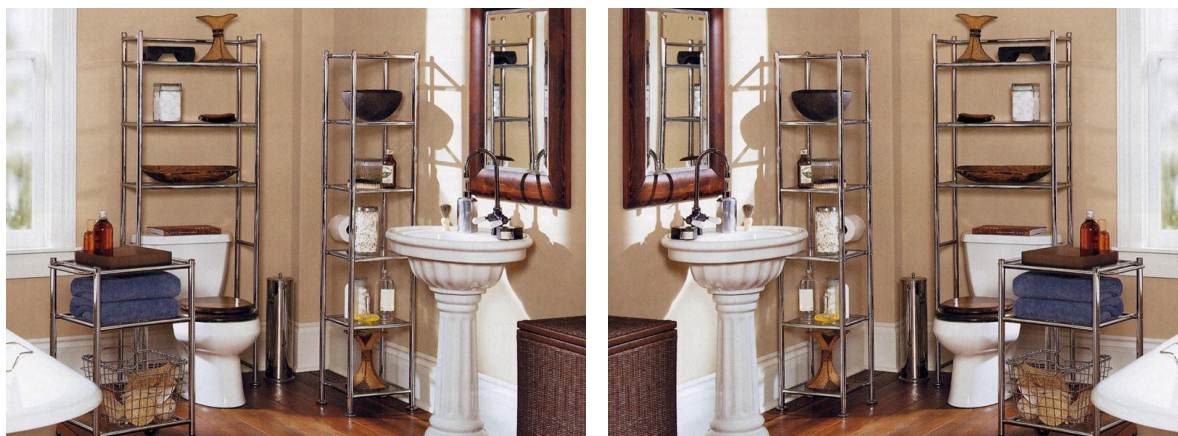
Figure 2. Example of images used in the Object Naming Task (original on the left and flipped on the right).

Participants viewed photographic images of scenes with simulated hemianopia for 4 seconds, after which the image disappeared and participants verbally listed all the objects that they could remember seeing in a particular scene. Participants were encouraged to list as many objects as they could remember. The responses were recorded using a voice recorder. The stimuli were 80 images of natural indoor and outdoor scenes (see example Figure 2) taken from Clarke, Coco & Keller (2013). The images were divided randomly into two sets. Each of the images in the two sets was also flipped to avoid any left/right bias. Therefore we had four sets in total (Original Images Set 1, Original Images Set 2, Flipped Images Set 1, and Flipped Images Set 2). If participant were tested with Original Set 1 on the first session, they would be tested with Flipped Set 2 on the second session, similarly if they saw Flipped Set 1 on the first session they would see Original Set 2 on the second (the full randomisation is shown in table 1 in the supplementary materials). We simulated hemianopia while participants were doing this task, in exactly the same way as in the five-day repeated exposure task. Participants who experienced left hemianopia in the first session experienced right

simulated hemianopia in the last session, and vice-versa. Thus in this task we had two hemianopia types (Left, Right), two image types (Original, Flipped), and two image sets (Set One, Set Two). For the purpose of data analysis none of these variables were of theoretical interest so we collapsed across them and only included just one independent variable: Session (1 vs. 2).

Results

Repeated Exposure Task Performance.

Reaction Time. RTs are shown in Figure 3. RTs were log transformed before they were entered into the model. Although we use terms sighted and blind side in the normal viewing condition, we essentially mean left and right side of the display. As expected, RTs are faster for easy search, and they improve over the five sessions. RT is faster when the target is in the sighted field, and simulated hemianopia slows search. To confirm the reliability of this pattern, a multiple regression was run to predict RT from Session (1 to 5), Viewing Type (Normal Viewing, Simulated Hemianopia), Target Side (Sighted, Blind, Absent) and Search Difficulty (Easy, Hard). These variables predicted RT, [F (4, 1015) = 290.18, $p <$ .001, R^2 = .53], with all four variables accounting for significant variance, [Session (Beta = -0.10, p < .001), Viewing Type (Beta = -0.38, p < .001), Target Side (Beta = 0.40, p < .001) and Search Difficulty (Beta = 0.59, p < .001)].
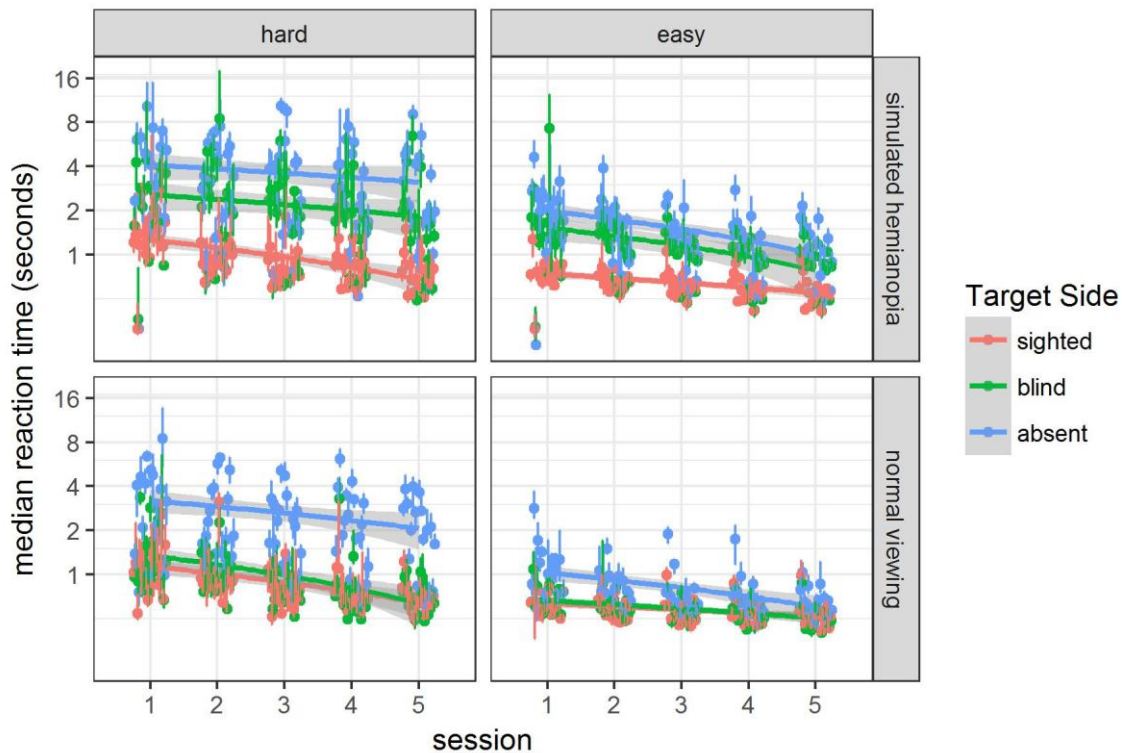
Figure 3. Mean of the median Reaction Times for the Simulated Hemianopia and Normal Viewing condition shown for two difficulty levels (Easy and Hard) and three target positions (target in the Sighted field, Blind field and target Absent trials) and five consecutive sessions. Y axis is on a log transformed scale. Error bars represent first lower quantile and third upper quantile.

Accuracy. As can be seen from Figure 4, accuracy shows a similar pattern to RT, with higher accuracy for easy search, and steady improvement over the sessions. Accuracy is also lower under simulated hemianopia conditions. Accuracy is higher in the target absent over present condition because of a tendency for participants to respond that the target is absent when unsure. For completeness, and to confirm the reliability of this pattern, a multiple regression was also run to predict Accuracy from Session (One to Five), Viewing Type (Simulated Hemianopia, Normal Viewing), Target Side (Sighted, Blind, Absent) and Search Difficulty (Easy, Hard) [$F_{(4, 1015)} = 94.00$, $p < .0005$, $R^2 = .27$]. All four variables contributed to the model, [Session (Beta = .03, p < .001), Viewing Type (Beta = .06, p < .001), Target Side (Beta = .03, p < .001) and Search Difficulty (Beta

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= .15, p < .001)]. Performance in the easy condition is clearly close to ceiling, however, and the results should be interpreted only in conjunction with the reaction time data.
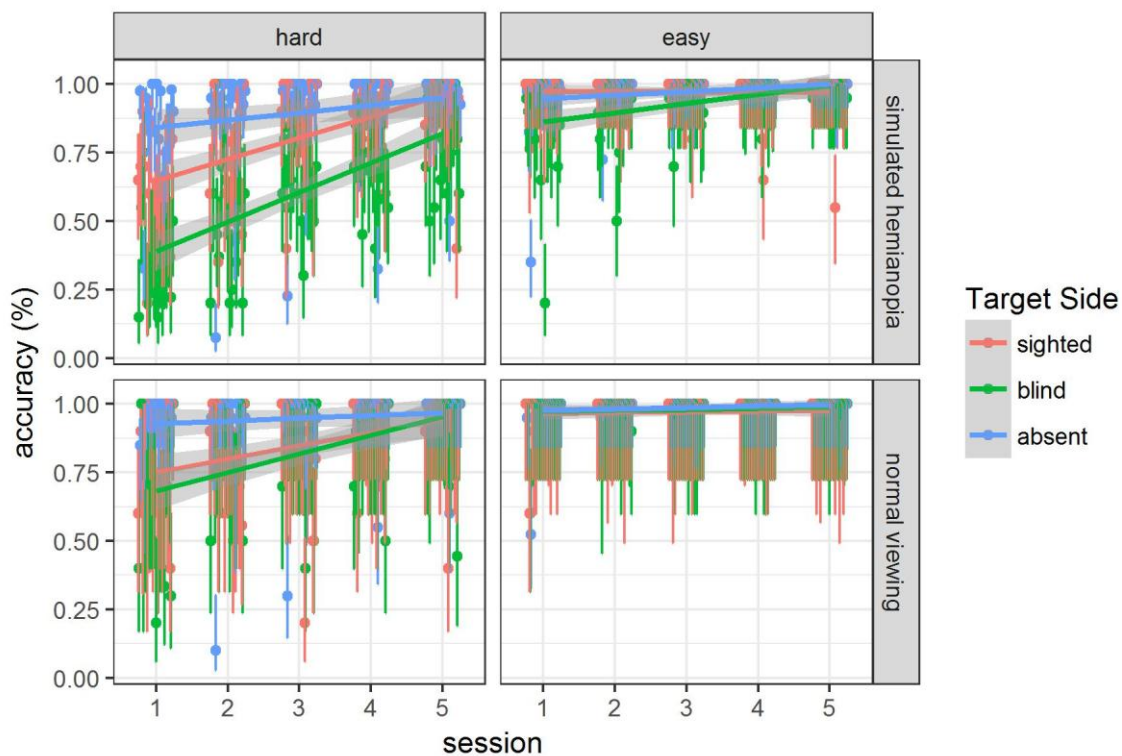

Figure 4. Mean accuracy for the Simulated Hemianopia and Normal Viewing condition shown for two difficulty levels (easy and hard) and three target positions (target in the sighted field, blind field and target absent trials) and five consecutive sessions. Error bars represent 95% confidence intervals based on binomial distribution.

Eye movement behaviour in the repeated exposure task. The reaction time and accuracy measures establish that participants improved their search performance over sessions. Can this improvement be explained by more efficient eye movements? The trials that best address this question are target absent trials when the target is easy to spot on the background. In this condition, eye movement behaviour can be unambiguously categorized as either efficient or inefficient: the target can easily be spotted in the periphery, so on easy trials participants can ascertain that it is not present and direct their eye movements towards the blind side. Any eye movements towards the sighted

side can be considered inefficient, because they provide no new information and increase the amount of the array obscured by the mask.

Figure 5 depicts the mean horizontal (*x*) position of the first eight fixations for each participant over the target absent trials across each of the five sessions. Negative values represent the masked side of the display. Over the course of the five sessions, participants increasingly directed their attention to the (initially) blind side of the display, and did so earlier in the trial. The shift in the distribution towards the negative side as session number increases is a particularly notable in the easy condition. To verify this, we carried out a 2x2x2 repeated measure ANOVA on the *x* position of fixation with Viewing Type (*Simulated Hemianopia, Normal Viewing*), Search Difficulty (*Easy, Hard*), and Session (1 vs 5) as factors. For simplicity, we have collapsed across fixation number (one to eight) and only analysed fixations from the first and last session. One participant did not have minimum of eight trials with eight fixations so was excluded from further analysis. We found a significant main effect of Search Difficulty [$F(1,15)=37.46$, $p<.001$, $\eta_p^2=.71$], Viewing Type [$F(1,15)=16.17$, $p=.001$, $\eta_p^2=.52$], and Session [$F(1,15)=37.62$, $p<.001$, $\eta_p^2=.72$], and significant interactions between Difficulty and Session [$F(1,15)=28.89$, $p<.001$, $\eta_p^2=.66$], between Difficulty and Viewing Type [$F(1,15)=25.65$, $p<.001$, $\eta_p^2=.63$], and between Viewing Type and Session [$F(1,15)=44.54$, $p<.001$, $\eta_p^2=.75$], but no significant interaction between the three factors [$F(1,15)=1.80$, $p=.14$, $\eta_p^2=.11$].

To further look at the effect of repeated exposure, we carried out separate analyses for the *Normal Viewing* and *Simulated Hemianopia* conditions. In the *Normal Viewing* condition a 2x2 ANOVA with *Search Difficulty* and *Session* as factors showed that none of the main effects or interactions were significant (all p>.32). In the

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Simulated Hemianopia condition, however, the same analysis showed significant main effect of *Search Difficulty* [$F(1,15)=41.48$, *p*<.001, η_p^2 =.73], *Session* [$F(1,15)=49.19$, *p*<.001, η_p^2 =.77], and a significant interaction between the two factors [$F(1,15)=7.31$, *p*=.02, η_p^2 =.33]. To look at this interaction in the *Simulated Hemianopia* condition, we carried out a paired samples t-test for each difficulty level. This analysis showed statistically significant differences between group means *both* when the search was *Hard* [$t(15) = 4.56$, $p < .001$], and *Easy* [$t(15) = 8.33$, $p < .001$]. Our participants changed their strategy both in the Easy and Hard condition, but the interaction indicates that the shift to the blind field is much more pronounced in the easy condition.
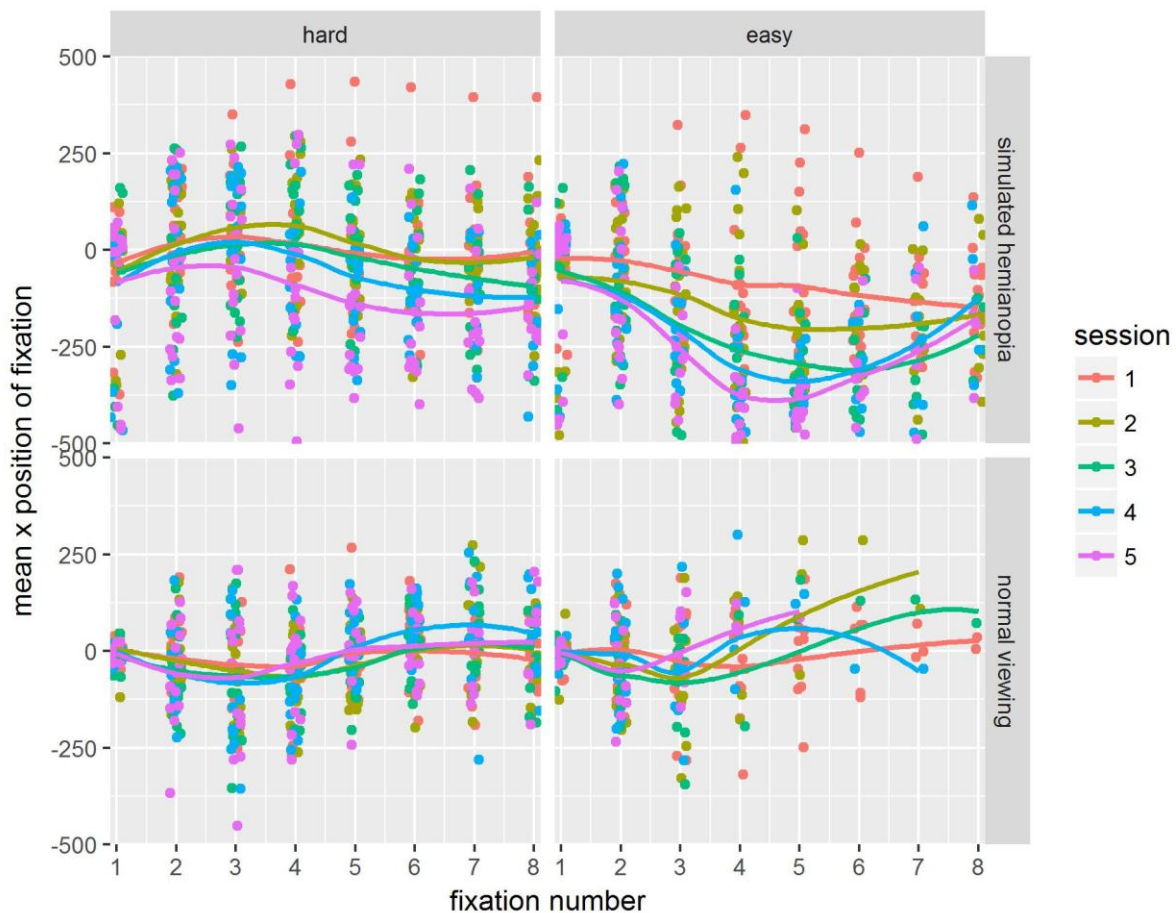

Figure 5. Mean position of the first eight fixations on the x-axis in the easy and hard condition, and for two viewing type levels (Simulated Hemianopia and Normal

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Viewing) in the target absent trials for the five consecutive days. Negative numbers on the Y-axis indicate the hemianopia side.
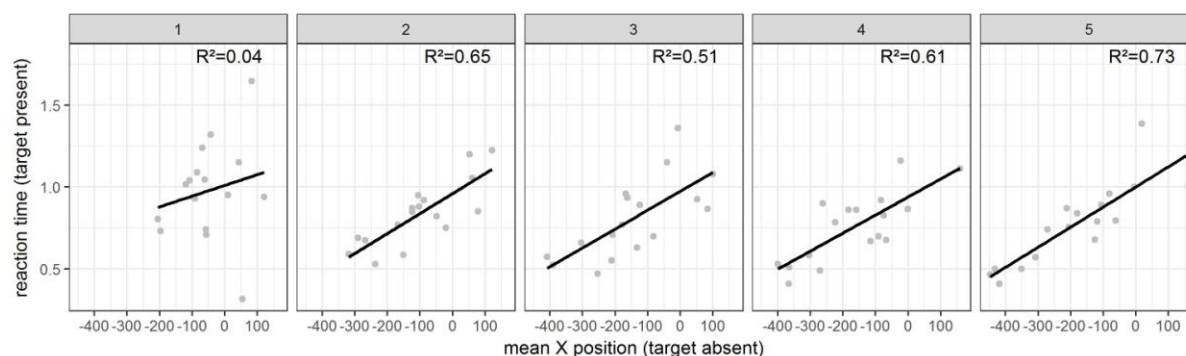

Figure 6. Correlation between mean fixation position of the first five fixations on the X-axis on the target absent easy trials and median reaction times (in seconds) on the target present easy trials, with the five panels representing five consecutive sessions.

We next measured the effect of strategy on search performance when the target was present. This analysis checks whether the eye movement strategy we are assuming is optimal in this task is, in fact, associated with faster search. We take the mean position on the X-axis of all fixations during target absent trials for each participant and correlate this measure with that participant's reaction time on the target present trials (irrespective of target side). We do this only for the easy search trials, because these are the trials in which we expect this strategy to provide the largest benefit. We excluded one participant from this analysis for having very long mean reaction time (over 7 seconds in the target absent easy condition). As is clear from Figure 6, participants who made more saccades towards the blind side when the target was absent were quicker to find the target when it was present. The benefits of searching the blind field early in the trial are evident in the first session and increase for the next four sessions.

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Although we did not do any follow-up testing with our participants beyond the week-long experiment, we correlated participant performance over the week and found that strategies stabilized towards the end of the week. There is small correlation between first and fifth session in terms of the mean eye movement position (target absent trials) for individual participants (r=.58, p=.02), but a very high correlation in performance between session 4 and 5 (r=.90, p<.005), suggesting strategy differences between participants becames very stable over the last two days of testing (see Figure 7).
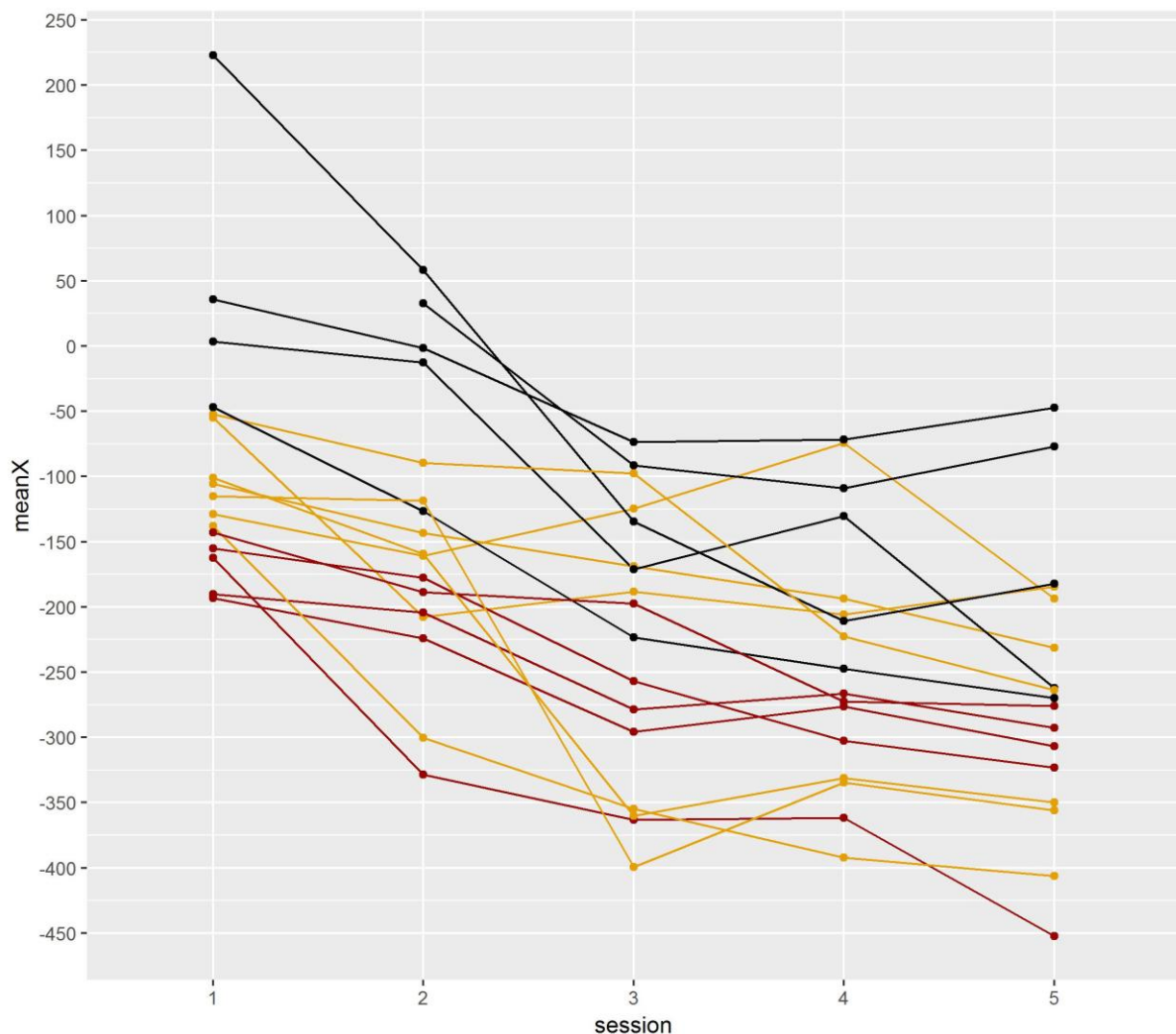

Figure 7. Mean position of first eight fixations in the easy condition target absent trials is shown for each of the five consecutive days. Negative numbers on the Y-axis indicate saccades towards the simulated-hemianopia side of the search array. Each line represents an individual participant. We colour coded the lines so the five

participants who started with larger saccades deep into the in the sighted field on the first day of the experiment are shown in black, five starting deepest in the blind field are shown in red and remaining participants are represented by orange lines.

As can be seen in Figure 7, most of our participants improved on the task later on in the week by shifting their fixations into the blind field. Yet, the degree of improvement varies. A few participants made eye movements that were increasingly deep into the blind field, but some did not move far from the midline. Some participants shifted their strategy abruptly very early in the week and some showed very gradual change. In this analysis we only looked at trials with minimum 8 fixations to reduce noise in the data. The participant missing data for the first session made only 40 fixations in this session's target absent parallel condition, while the average for the other participants was around 350 fixations. Together with low accuracy (35 % correct trials, compared to the rest of the group average, 95% correct trials) these data suggest the participant was guessing in this session. His accuracy and number of fixations in following sessions increased.

Detection Task Results

We included a detection task as a control to check whether performance improvements across sessions could be attributed only to eye movement strategies, or if perceptual sensitivity to the target also improved with repeated exposure. The accuracy data from the detection task on the first and last day of the repeated exposure group as well as control group results are shown in Figure 8. We only analysed data from 16 participants in the control condition, as data from one participant on Friday session was not recorded due to technical difficulties. As is clear from the Figure, participants perform better on the task in the second session, but this improvement is

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only modest in the control condition compared to the improvement we see following repeated exposure to the line segment search task. We calculated d' as a measure of participant's sensitivity to the target in this task. To overcome the problem of extreme values in our data (i.e. having the proportion correct be 1 in some participants in some conditions) we used the loglinear approach (Hautus, 1995). We added 0.5 to both the number of hits and the number of false alarms and added 1 to both the number of signal trials and the number of noise trials, before we calculated the hit and false-alarm rates.
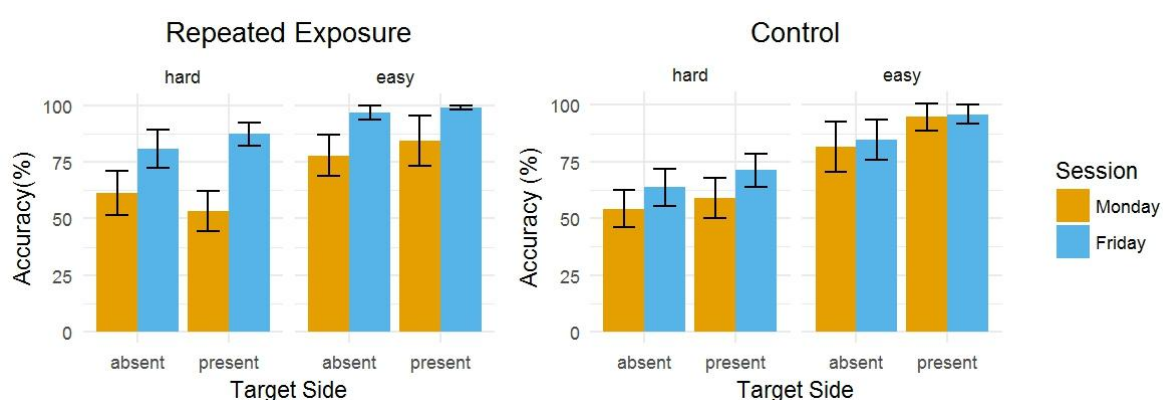

Figure 8. Accuracy data from the detection task shown separately on Monday and Friday for target absent and present trials and two levels of Search Difficulty. Left panel shows accuracy in Repeated Exposure group and right panel Control group. The error bars show 95% confidence intervals.

We carried out a mixed design ANOVA with one between group factor (Repeated Exposure vs. Control), and two repeated measures (Search Difficulty, Session). There was no significant effect of group [$F(1,31)=3.37$, $p=.08$, $\eta_p^2=.10$]. We found a significant effect of Session [$F(1,31)=59$, $p<.001$, $\eta_p^2=.66$] and Difficulty [$F(1,31)=202.67$, $p<.001$, $\eta_p^2=.87$]. There was also a significant interaction between Session and Group [$F(1,31)=23.91$, $p<.001$, $\eta_p^2=.44$], indicating larger improvements across session with repeated exposure to the stimuli. There was also an interaction of Difficulty and Group [$F(1,31)=5.10$, $p=.03$, $\eta_p^2=.14$], due in part to ceiling effects in the easy condition, but no

significant three way interaction [$F(1,31)=.25$, $p=.62$, $\eta_p^2 =.008$]. Overall, the results show that participants improved on the task in both groups, and this improvement was enhanced with intervening simulated hemianopia sessions.

Object Naming Results

To analyse mean number of objects named in the two groups, we carried out a 2x2 Mixed Design ANOVA with Session as a within-subjects variable and Group as a between-subjects variable. This analysis showed significant Group differences [$F(1,32)=6.43$, $p=.02$, $\eta_p^2 =.17$], and no significant effect of Session [$F(1,32)=.53$, $p=.47$, $\eta_p^2 =.02$]. There was a significant interaction between Session and Group [$F(1,32)=9.74$, $p=.004$, $\eta_p^2 =.23$], however, so we looked at the effect of session for each group separately. Paired sample t-tests showed that participants reported significantly more objects on Friday [*M*=5.17, *SD*=.79], compared to Monday [*M*=4.69, *SD*=.61; *t*(16)=2.68, *p*=.016] in the Repeated Exposure group. In contrast, participants did not report significantly more objects in the Control group on Friday [*M*=4.46, *SD*=1.10], compared to Monday [*M*=4.16, *SD*=.74; *t*(16)=1.63, *p*=.12].
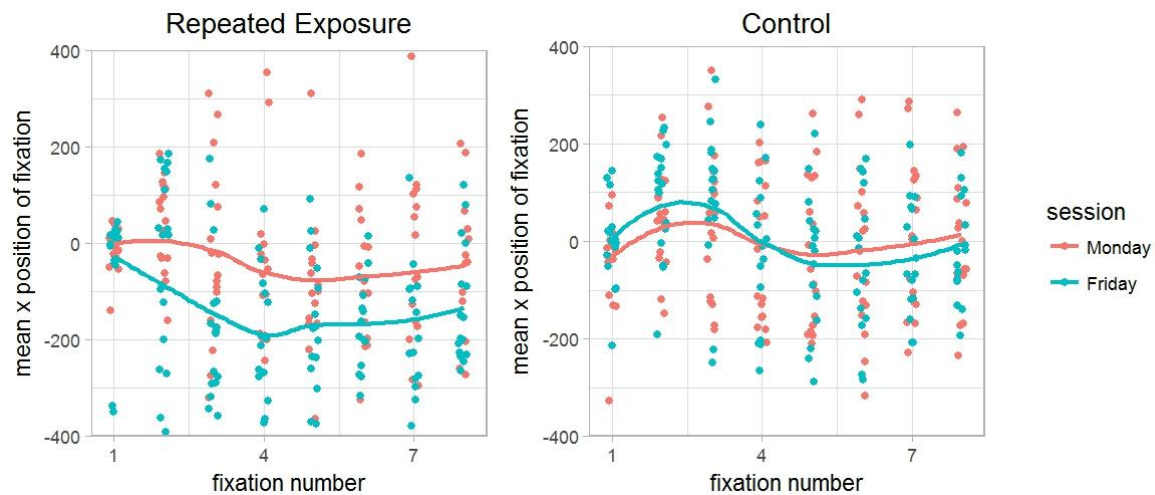
Figure 9. Mean position of fixation on the x-axis shown for the first eight fixations, separately for Monday (red) and Friday (blue) sessions. Zero on the Y axis represents middle of the screen, and the negative numbers extend to the field where mask was applied.

We then analysed the mean horizontal position of fixation (Figure 9). To simplify data analysis, we collapsed across fixation number (first eight fixations). A 2x2 Mixed Design ANOVA with Session as within variable and Group as between variable showed significant between-group differences [$F(1,32)=6.83, p=.01, \eta_p^2 =.18$], a significant effect of Session [$F(1,32)=6.29, p=.02, \eta_p^2 =.16$], and a significant interaction between Session and Group [$F(1,32)=11.93, p=.002, \eta_p^2 =.27$]. Paired sample t-tests indicated that participants moved further into the blind field in the second session [*M*=-159, *SD*=97], compared to the first session [*M*=-6, *SD*=165, $t(16)=3.63, p=.002$] in the Repeated Exposure group. The same analysis on the Control group indicated that participants did not move further into the blind field in the second session [*M*=23.63, *SD*=131] compared to the first session [*M*=-.69, *SD*=113, $t(16)=.83, p=.42$].

General Discussion

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Repeated exposure to a simulated visual field deficit can lead to the spontaneous development of a more efficient visual search strategy. We observed faster reaction times and higher accuracy following five consecutive days of repeating the search task. Faster and more accurate search can be partially explained by increased perceptual sensitivity to the target. However, participants' fixations progressively moved deeper in the blind field with every session, and this shift was seen both in the easy search condition, where this strategy was most effective, but also in the hard condition, to a lesser extent. Saccades into the blind field were strongly associated with improved search performance. Importantly, the improvements in eye movement strategy in the search task transferred to the object naming task. A control group that performed the object naming task on the first and last day, without any intervening exposure to the simulated deficit, did not change their search strategy, and did not name more objects in the second session.

Eye movements towards the sighted field provide no new information in the easy search condition; the target would be clearly visible in peripheral vision if it were present, so eye movements towards the sighted field substantially *decrease* information by shifting the simulated deficit across a larger proportion of the search area. In our previous study, using the same search stimuli (Nowakowska et al., 2016) we found that participants frequently directed eye movements towards the sighted field even though the target was obviously absent, exhibiting surprisingly inefficient search behaviour. In the current study, we generally replicate this finding in our first testing session, with many eye movements directed towards the sighted field. There is, however, a slight difference in the results of the two experiments, with a slight bias towards the blind field in the current experiment, and a slight bias towards the sighted field in

Nowakowska et al. (2016). While this may seem contradictory, the individual differences we observe in both these studies are worth noting. In the current study, several participants exhibited near-optimal eye movements even in the first session, whereas others did not. We observed a similar range of individual differences in eye movement strategies in a third recent study (Nowakowska, Clarke & Hunt, 2017) in which the logic was similar, but there was no simulated hemianopia. The results of all three of these studies demonstrate a high degree of inter-subject variability. We have therefore been careful to depict the individual participant means in figures describing eye movement behaviour, and avoid making broad conclusions about "people's" search strategies. That said, these data match our previous results in demonstrating that we do not have an *a priori* default bias to fixate locations that provide us with the most information, as suggested by Najemnik and Geisler (2005, 2008).

While most people do not begin the week with a clearly optimal eye movement strategy, as the week progresses, and good performance is rewarded, our participants become less variable in their strategies and more of them exhibit eye movements that could be classified as efficient. In other words, participants gradually figure out the most effective strategy and this strategy helps them perform better in each session. In training studies of patients with hemianopia (Schuett, 2009; Jacquin-Courtois, 2012), participants are typically given specific instructions and are encouraged to use a particular strategy. We found that in some healthy observers with simulated deficit, an efficient strategy can develop spontaneously simply through exposure to the deficit and practice with a specific search task. These results could lend partial support to optimal search model (Najemnik & Geisler, 2005; 2008) postulating eye movements are directed to locations that are expected to lead to the highest possible information gain.

If the participants were optimal in the strictest sense, the mean x-position should be shifted deep into the blind side from the very start of the trial, yet this shift only happens after the initial few fixations. We think a more plausible alternative is that participants' eye movements are largely consistent with the stochastic model (Clarke et al. 2016). In this model, each eye movement during search is randomly selected from the population of eye movement vectors that a participant tends to make from that region of the search array. Thus while the saccade selection process is random, the population of saccade vectors is constrained, making some locations more likely to be fixated than others (see also Clarke et al., 2017). These constraints on the population of vectors, we argue, come from a combination of motor, perceptual, and attentional biases that have evolved or develop gradually to make "random" search more efficient. In the current experiment, we would argue that the population of saccade vectors is gradually constrained by the reward of improved search times, leading to a slow and steady increase in the efficiency of eye movement behaviour. Although participants change their strategy most clearly in the easy condition, we also see shift towards the blind field when search is difficult, although to a lesser extent. This behaviour does not harm the performance, as participants have to search the whole display in order to find the target.

Patients with hemianopia tend to spend more time overall looking into the side associated with the deficit on a free viewing task (Ishiai et al., 1987), the pattern we see towards the end of the week (in the easy condition). Why did we not see this strategy in the first session? Firstly, our participants may need time to adjust to the deficit, because simulated hemianopia is a very unusual experience. Secondly, in our initial experiment

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(Nowakowska et al., 2016), and first session of the current experiment, participants did not receive any reward for good search performance.

One critical consideration is the extent to which conclusions drawn from any experiment using simulated hemianopia could be applied to patients with visual field deficits. In considering this, it is important to keep in mind that the goal of our study was to understand whether healthy individuals adopt effective eye movement strategies to compensate for visual deficits. There is an urgent need for more pre-morbid data on how we can expect the visual system to be affected by a loss of information, to provide a contrast with how the injured brain responds. By documenting the longer-term change in eye movement strategies, the range of individual differences in our sample, and the fact that these individual differences get more stable over time, we have provided important context for understanding the eye movement behaviour of patients. For this purpose, a perfect simulation of the wide-ranging effects of brain injury is less critical than having a uniform method for comparing compensation strategies across healthy individuals.

That said, it is important to keep in mind that simulated hemianopia differs from the effects of brain damage in many respects. Visual deficits are not uniform in their effects but depend on the specific damage that caused them. Due to decussation of nerve fibres, post-chiasmatic lesions of the visual pathways result in homonymous field defect. That is, the blindness appears to be the same in both eyes, both in terms of the visual field location and extent. Weiskrantz and colleagues have demonstrated that in cases of post-geniculate lesions, some visual capacities may remain for detection/discrimination of visual features with or without any acknowledgement of visual awareness, termed blindsight (Weiskrantz, 1986). The neuronal basis for such capacities are often presumed to be visual processing that by-passes the direct geniculo-striate pathways.

Evidence for such projections comes from functional imaging studies in humans and in non-human primates. In those with pre-geniculate lesions and in some patients with occipital lesions, when the lesion has extended anteriorly to the Lateral Geniculate Nucleus, there is limited ways for the visual information to be transmitted to higher visual areas for processing and therefore there is no evidence for blindsight. Indeed, some recent studies have shown that up to 30% of hemianopic patients may show no blindsight abilities (see for example Sahraie, Trevethan, MacLeod, Urquhart, & Weiskrantz, 2013). The current method of simulating hemianopia works by completely removing all the visual information from one half of the display screen in a gaze contingent manner. This method of "hard-edge" hemianopia, is a good approximation of what happens in this sub-group of hemianopic patients.

Although in the current study we do not provide participants with any "residual information", in Nowakowska et al. (2016) we found no difference in gaze strategy when information on the position of the stimuli was available on the "blind" side; participants continued to ignore location pointers and direct most of their saccades to the sighted side, even though using location information would allow them to target the stimuli more precisely. Only when low spatial frequency identity information was supplied did participants direct more saccades to the blind field. In hemianopia, the extent of brain injury is one known predictor of the ability to spontaneously compensate for patient's visual field deficit (see for example a study of 70 patients by Zihl, 1999 or Tant at all., 2002). Results of the current experiment, a related visual search experiment performed in our lab (Nowakowska et al., 2017), and experiments looking at other modalities (memory, target detection, throwing; Clarke & Hunt, 2016) consistently showed large individual differences between participants in

terms of the ability to adjust strategy to task difficulty. On the basis of these cumulative findings we could speculate that some variability in the compensatory strategy development or its lack could also be explained by individual differences.

In the present study, all participants were exposed to both simulated hemianopia and normal viewing conditions, so it is impossible to dissociate the effects of masking from those of repeatedly performing the task. It was for this reason that we included the simple detection task in the first and last session, to estimate the extent to which improvements in performance from the first to the last session were due to changes in eye movement strategy versus better detection of the target. It is clearly a combination of both, and it would have been interesting (in retrospect) to include a group who searched for the target without a mask. In related work without masks (Nowakowska, Clarke and Hunt, in preparation), we find evidence that healthy observers tend to develop better search strategies over time, so we do not believe this is specific to hemianopia, but reflects a more general pattern: eye movement strategies are generally sub-optimal, and can improve spontaneously to some extent, but remain far from optimal in most individuals. This has clear relevance to how we rehabilitate patients with visual deficits.

In our investigations in healthy adults reported here, we note a high correlation between performance on the fourth and fifth sessions on the task, suggesting that those participants who have not developed an optimal strategy by day five are very unlikely to change their strategy later on. It is likely that a combination of both the premorbid variability we have documented here, as well as loss of specific connectivity after the lesion, underlies the patterns of recovery/plasticity in patients such that some may recover spontaneously whereas others, irrespective of the time duration post-injury, remain impaired. An important remaining question is the extent to which specific

instructions or interventions can facilitate better strategies specifically in this sub-population of individuals with persistently poor eye movement strategies. Another important question is the extent to which such training transfers to real world contexts, which usually involve a far more complex visual environment, offering many competing demands on the subject for navigation, orientation and visual processing.

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Highlights:

We simulated hemianopia in healthy observers completing a search task for five consecutive days with reward for good performance
We observed more efficient, yet far from optimal, search strategies with practice
Improvements in search strategy generalized to a novel task