Inefficient search strategies in simulated hemianopia

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Abstract

We investigated whether healthy participants can spontaneously adopt effective eye movement strategies to compensate for information loss similar to that experienced by patients with damage to visual cortex (hemianopia). Visual information in one hemifield was removed or degraded while participants searched for an emotional face among neutral faces or a line tilted 45° to the right among lines of varying degree of tilt. A bias to direct saccades towards the sighted field was observed across all four experiments. The proportion of saccades directed towards the "blind" field increased with the amount of information available in that field, suggesting fixations are driven towards salient visual stimuli rather than towards locations that maximize information gain. In Experiments 1 and 2, the sighted-field bias had a minimal impact on search efficiency, because the target was difficult to find. However, the sighted-field bias persisted even when the target was visually distinct from the distractors and could easily be detected in the periphery (Experiments 3 and 4). This surprisingly inefficient search behaviour suggests that eye movements are biased to salient visual stimuli even when it comes at a clear cost to search efficiency, and efficient strategies to compensate for visual deficits are not spontaneously adopted by healthy participants.

Key words:

Visual search, optimality, blindsight, hemianopia

To find a target among distracters, our eyes perform frequent eye movements (saccades) to bring new regions of interest to the high-resolution fovea. Saccade endpoints during search have been shown to be determined by bottom-up image properties, such as colour, object size, and orientation (Rutishauser & Koch, 2007); spatial arrangement (Pomplun, Reingold, & Shen, 2003); and top-down factors, such as knowledge or prior experience (Chen & Zelinsky, 2006; Neider & Zelinsky, 2005; Zelinsky, 2008), and the fine interplay between all of these (Rutishauser & Koch, 2007). Above all, an optimal visual system should integrate all the available information to minimise the number of saccades needed to find the target. Search is typically studied under optimal conditions, when the search items are fully visible and equally accessible to the observer. Much less is known about the efficiency of our eye movements when bottom-up information is degraded or missing altogether. A unique opportunity to approach this question of efficacy in sub-optimal conditions comes from studying the effect of visual field deficits on scanning behaviour.

Homonymous hemianopia occurs when vision is lost in half of the visual field in both eyes due to post-chiasmatic brain injury. Not surprisingly, patients with such lateralized field deficits tend to display different scanpaths compared to controls. When scanning the visual world for a target object, patients perform frequent refixations and imprecise saccades, resulting in disorganised scanpaths, longer reaction times, and decreased ability to find the targets altogether (Meienberg, Zangemeister, Rosenberg, Hoyt, & Stark, 1981; Zihl, 1995; Zihl, 1999). While viewing naturalistic scenes, patients tend to fixate different spatial regions, make more fixations of shorter duration compared to healthy observers, and spend more time overall on the hemianopic side (Ishiai, Furukawa, & Tsukagoshi, 1987; Pambakian, Wooding, Morland, Kennard, &

Mannan, 2000). In a laboratory visual search task patients tend to begin exploring the image on the side of the lesion (Chedru, Leblanc, & Lhermitte, 1973), yet nonhuman primates with unilateral ablations of V1 tend to start their visual exploration from their intact visual field (Yoshida, Itti, Berg et al., 2012) on a free viewing tasks. Whether the bias to search first the blind side is present seems to be heavily influenced by the task type and whether it is a laboratory or naturalistic task (Hardiess, Papageorgiou, Schiefer, & Mallot; Iorizzo, Riley, Hayhoe, & Huxlin, 2011; Martin, Riley, Kelly, Hayhoe, & Huxlin, 2007).

An important question is whether the differences in oculomotor behaviour seen in these patients are purely a consequence of the visual field deficit itself or are a result of damage to functionally related brain areas. To address this, Tant, Cornelissen, Kooijman and Brouwer (2002) simulated hemianopia in a group of healthy subjects using gaze-contingent displays. This involves on-line tracking of eye movements, and with reference to the tracked gaze position, replacing the part of the screen corresponding to the blind field with a window of the same properties as the background. In other words, whenever the observers move their eyes, the "blindness" moves with them. Tant et al. (2002) tested healthy subjects on a dot-counting task (a paradigm adapted from Zihl, 1995, 1999) under free viewing and simulated hemianopia conditions, and observed scanning strategies similar to those of hemianopic patients. Relative to controls, observers with hemianopia and simulated hemianopia had longer search times, less systematic and longer scanpaths, displayed more fixations, and were less accurate in detecting stimuli. Comparable performance in simulated and acquired hemianopia implied that defective eye-movements were primarily (but not entirely, see Schuett, Kentridge, Zihl & Heywood, 2009b) elicited by the visual deficit itself. The gaze-contingent paradigm initially devised by Tant and colleagues was later used to investigate several other effects of visual deficits, for instance: temporal dynamics of the adaptation to the visual field deficit (Simpson, Abegg & Barton, 2011), reading and visual exploration (Schuett, Kentridge, Zihl, & Heywood, 2009a, 2009b) and line bisection errors (Schuett, Kentridge, Zihl, & Heywood, 2009c).

Some patients spontaneously adopt some compensatory strategies (Zihl, 1999), and those who do not can be trained to do so. One strategy to compensate for a lateralized field deficit is to saccade as far into the blind field as possible to maximise the proportion of the search area that falls in the sighted field (Pambakian, Currie, & Kennard, 2005; Pambakian, Mannan, Hodgson, & Kennard, 2004). Encouraging patients to utilize these strategies in real life improves general functioning (based on self-reports, Mannan, Pambakian, & Kennard, 2010; Zihl, 1981). Real-life improvements were demonstrated by Bahnemann et al (2015), who compared hemianopia patients with high and low hazard detection rates in a simulated driving task on a number of eye and head movement measures. Patients with better hazard detection had larger saccades towards the blind field, a wider distribution of fixations along the horizontal meridian, and a higher number of fixations on the blind side. Similarly, large eye movements, and specifically eye-movements directed towards the blind part of the visual field, improved search for specific items in a supermarket (Kasneci et al., 2014), and collision avoidance (Papageorgiou, Hardiess, Mallot, & Schiefer, 2012).

Hemianopia is typically simulated by completely removing all the visual information from part of the visual field. This is not entirely consistent with the effects of damage to post-geniculate visual pathways; the loss of vision in the contralateral visual field is often accompanied by residual visual capacity (known as *blindsight,* Weiskrantz, 1986). Patients with blindsight can discriminate not only the presence or absence of a stimulus, but also other properties of the stimuli such as position, orientation, movement, and emotion, and can even distinguish between complex images (Riddoch, 1916, 1917; Trevethan, Sahraie, & Weiskrantz, 2007a, 2007b). Patients with visual field defects are often able to detect and discriminate some visual features within their blind field even when they are unaware of the target presence (Weiskrantz, 1986). Recently, it has been shown that in some 70% of hemianopic patients, low spatial frequencies can be processed (Sahraie, Trevethan, MacLeod, Urquhart, & Weiskrantz, 2013). In addition, significant detection of stimuli of social significance such as facial expressions of fear and anger have been reported for stimuli presented within the field defect (Pegna, Khateb, Lazeyras, & Seghier, 2005) and it is claimed that such expressions predominantly rely on low spatial frequencies (Bannerman, Hibbard, Chalmers, & Sahraie, 2012). Blindsight is thought to be subserved by secondary visual pathways bypassing the geniculo-striate projection, such as the retinotectal pathway that projects from the retina directly to the superior colliculus of the midbrain, a structure involved in eye movement control. It is therefore reasonable to expect that patients would be able to direct visually-guided eye movements into the blind field to some extent, and indeed this basic principal has been clearly established in nonhuman primates with unilateral ablations of V1 (Mohler & Wurtz, 1977; Yoshida et al., 2012). In cases where residual visual capacity exists, large eye movements directed deep into the blind field may not be as efficient as relying on this residual capacity to guide eye movements to potential targets.

Even in the absence of any information from the blind field, a strategy of making large eye movements into the blind field would be sub-optimal in many circumstances.

For example, if the target is in the sighted field, or the locations of potential targets in the blind field are constrained or predictable, then a large saccade into the blind field will increase search time compared to a search path that uses available visual information to prioritize more likely target locations. An influential model of visual search proposes that visual information is integrated across the entire visual field, and eye movements are executed to locations that are most efficient for finding the target (Najemnik & Geisler, 2005). This model implies that healthy observers are optimal in visual search, in the sense that each eye movement is executed to the location that will maximally decrease uncertainty about the target location. Consistent with this idea, Janssen and Verghese (2015) recently reported that healthy participants were able to adopt a deliberate strategy of making eye movements to a target object hidden under gaze-contingent artificial scotoma in the presence of visible distractor. However, viable alternatives to this model of search have been suggested. Clarke, Green, Chantler and Hunt (in press) demonstrated that a stochastic model of fixation selection can also match human search performance and is far less computationally taxing. Optimality in eye movements has also been called into question by recent examples of complete failures of healthy human observers to adopt efficient eye movement strategies (Clarke & Hunt, 2016; Morvan & Maloney, 2012; Verghese, 2012). It is therefore unclear whether healthy participants (or patients) can be reasonably expected to spontaneously adopt an optimal strategy to cope with visual deficits, or if they require specialized training.

Our main goal in these experiments was to characterize the eye movement strategies spontaneously adopted by healthy human observers in response to simulated visual deficits. In the first two experiments, participants searched for a target emotional expression in a group of neutral face distractors. Information to the left or right of the direction of gaze was either partially or totally removed. These experiments establish eye movement tendencies in difficult search under conditions of partial or total information loss. Contrary to patients tested on a visual search task before (Chedru et al., 1973), our healthy participants were biased to direct eye movements towards the sighted field over the "blind" field. This bias diminishes with increased amount of information available in the blind field. However, when search is difficult because the target is difficult to identify in the periphery, there is no advantage to searching the blind field first, as each item must be fixated to determine if it is or is not the target (as demonstrated in Experiment 2). In Experiments 3 and 4, therefore, we directly manipulated the visibility of the target, using search for a line segment at a specified orientation hidden amongst distractor line segments. Target visibility was manipulated by varying the heterogeneity of the distractor line segment orientations. The bias to search the sighted field first persisted even when the target was easy to spot in the periphery, suggesting search strategies are suboptimal, and not sensitive to the amount of potential information that can be gained by moving the eyes into the blind field.

Experiment 1

The gaze-contingent method of simulating hemianopia in healthy people used previously (e.g. Tant et al., 2002) removed *all* visual information from the "blind" field. With a view to extend the present method to hemianopic patients in future studies, in the first experiment we selected experimental conditions that are more likely to drive saccadic eye movement in the patient group, namely, the detection of emotional information present in low spatial frequency components of faces (Bannerman et al., 2012; Sahraie et al., 2013). The search items to one side of the point of gaze a) were removed entirely, b) had high spatial frequency information removed, c) were replaced with dots to mark their locations, or d) were unmodified (control). We examined eye movement metrics under these different conditions, including the bias to make eye movements towards the sighted versus the "blind" field. The results provide insight into how search is influenced by partial information in the blind field, a condition that may be a better representation of the blind field in a substantial subset of patients with hemianopia.

Method

Participants. Thirty-three participants (females=14; age range =20-40; mean age=24.7 ± 4.34) completed the experiment. All reported normal or corrected-to-normal vision. Four participants were excluded from further analysis: one for unusually long fixations (median>2 sec), one participant only fixated the central fixation cross position, and two participants had accuracy rates at chance level.

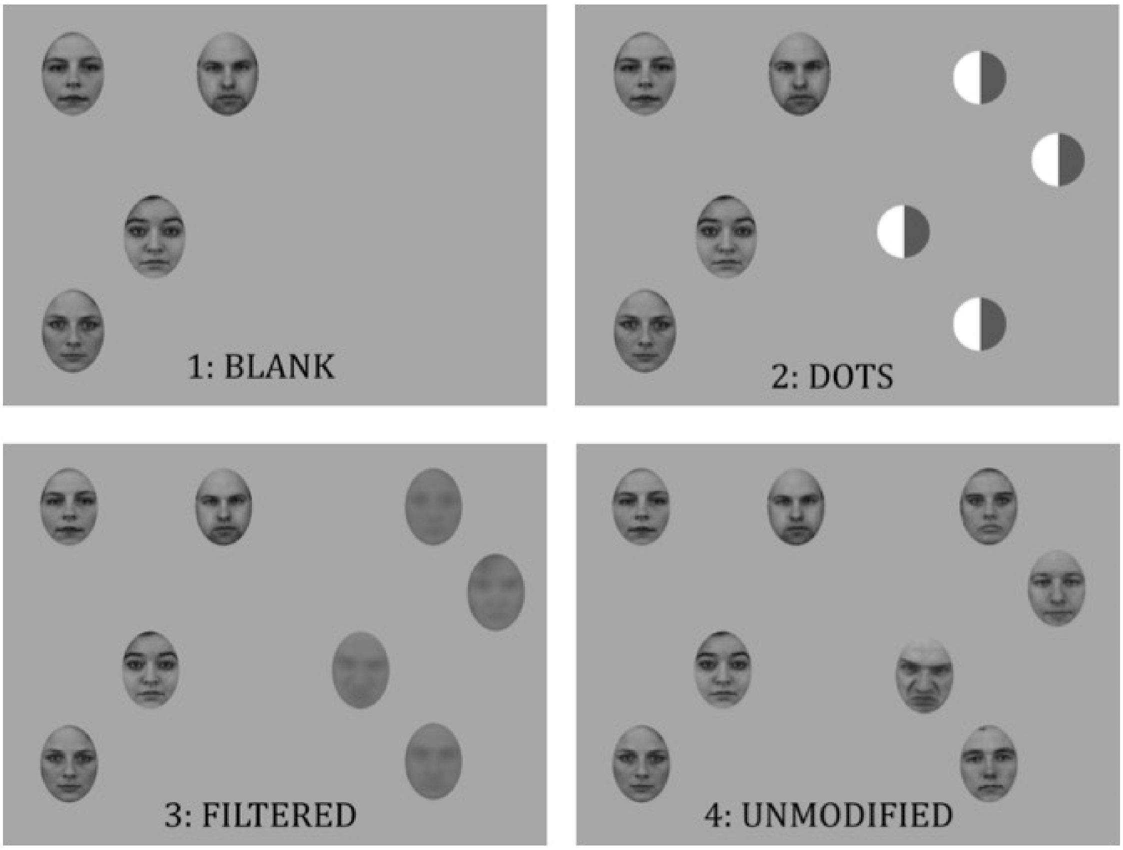

Figure 1. Example of stimulus sets in the four right mask conditions when fixation falls at the centre of the screen. Note that the actual dots in the *Dot* condition were two shades of grey (not black and white as we refer to them in the text for simplicity) that taken together equalled the luminance of the background. We increased luminance in the example stimulus above to make the dots more visible for the reader.

Materials. The face stimuli were drawn from a set of 10 male and 10 female greyscale face images (20 identities x 2 emotions) taken from the publicly available Karolinska Directed Emotional Faces set (KDEF: Lundqvist, Flykt, & Ohman, 1998). Each of the images subtended 3.2° x 5.1° (2.5 x 4cm at a viewing distance of 45 cm) after being cropped to remove the hair. Each of the 40 images was also filtered using a lowpass spatial filter to create the stimuli for the gaze-contingent filtered condition. The low spatial frequency cut-off was 2 cycles per degree (for the exact method of filtering and normalizing images refer to Bannerman et al., 2012). We decided to include the 2 c/° cut-off because the remaining information was in the range of the optimal frequencies for detection and awareness in blindsight reported by Sahraie et al. (2010, 2013) and comparable to the parameters applied in previous studies by Vuilleumier, Armony, Driver and Dolan (2003) and Bannerman et al. (2012). Previous work also indicated that participants were able to correctly classify the emotion expression at this low spatial frequency range (Bannerman et al., 2012). The stimuli in the Dot condition consisted of black and white dots subtending 2° (1.6cm) (13.9cd/m^2 black half, 20.8cd/m^2 white half). Search items were located in eight random positions on a 6x4 invisible grid (four items on each side of the screen). In all four conditions the stimuli were located on a uniform grey background. The mean luminance of face images, dots and background were matched to 17(±1) cd/m^2.

Each participant was tested under four experimental conditions: *Blank*, *Dot*, *Filtered* and *Unmodified* (control). Under the three masked conditions (*Blank*, *Dot* and *Filtered*) 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 grey background (*Blank* condition); black and white dots representing the spatial location of the faces (*Dot* condition); or the low spatial frequency version of the face (*Filtered* condition), respectively (See Figure 1 for the example of stimuli). In the *Unmodified* condition (control) eye movements were sampled but no mask was applied.

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 length of the entire system's delay was 1.5ms (time taken from registering a new sample to screen update). 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.

Procedure. On arrival at the laboratory each participant was asked to read and sign a consent form and was seated alone in a small dimly lit room. Participants were told that they would be doing a search task and their eye movements would be recorded while performing the task. Participants were then screened for eye-dominance and seated in front of a computer screen, their heads resting in a chinrest. To help our participants distinguish between angry and neutral faces (and thus increase accuracy) we first familiarised them with the stimuli. We presented participants with an overview of all the images of unfiltered face stimuli arranged in two labelled columns (neutral expressions on the left and angry expressions on the right) by twenty rows (representing ten male and ten female identities). Participants were encouraged to look at the stimuli for as long as they wanted before starting the computer based task. For the search task, participants were told they would see eight faces randomly positioned on the screen and their task was to indicate, by pressing either the left or right arrow key on the keyboard, whether an angry face was presented among neutral faces.

The masking condition (*Blank*, *Dot*, *Filtered* and *Unmodified*) and the location of the mask (left or right) were blocked and the block order was randomized. Participants were informed of the condition before they started each block. Participants were instructed to press a space bar with their left hand to initialize each trial and to press the arrow keys with their right hand. Each trial consisted of a black fixation point (letter x) subtending 1.5x2.5cm (1.9°x3.1°), presented at the centre of the computer screen. On the press of a space bar, the fixation point was immediately replaced by the search array, with the mask applied according to the condition. For example, in the right-side mask 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 display was replaced with the initial fixation point for the next trial 200ms after the left or right arrow key was pressed. Participants completed eight blocks of 32 trials (256 trials total): two blocks for each of the four mask conditions, one block masked to the left and one to the right (no mask was applied in *Unmodified* condition, but two blocks were run to match the number of trials in the other conditions). 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. Before each block of trials participants underwent a nine-point eye movement calibration sequence. Participants were not given any information about hemianopia or simulated hemianopia until they finished the experiment.

Results

To investigate how the different mask-types influence search performance we first carried out an analysis of variance (ANOVA) on reaction time and accuracy. To characterise scanning behaviour we also analysed the number of fixations per trial, saccade amplitude, and the proportion of saccades directed into the blind versus sighted field. For these two latter measures we analysed the target absent trials only, to ensure all saccades in the analysis were search-related and not directed toward the target itself. In these and all subsequent analyses, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity wherever necessary. To keep our analyses simple and hypothesis-driven, all additional analyses are included in the supplementary information and will be referred to in the text when relevant[i].

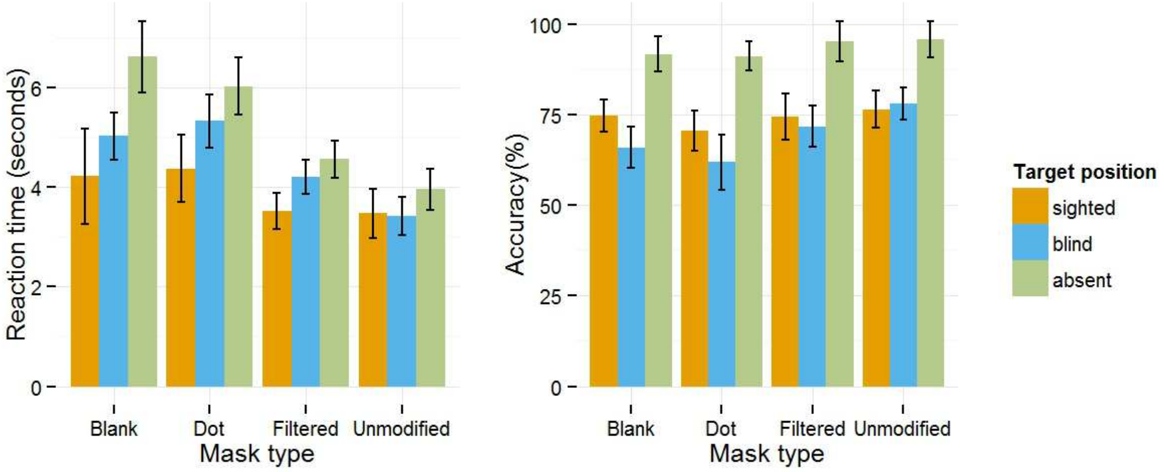

Figure 2. Median Reaction time (left panel) and mean accuracy (right panel) for the four mask types split by target position. Error bars represent 95% confidence intervals in this and all subsequent figures.

Reaction time and accuracy. Median RT on correct trials was calculated for each participant and was analysed using a 4x3 repeated measures ANOVA with Mask Type (*Blank*, *Dot*, *Filtered*, *Unmodified*) and Target Position (*Sighted*, *Blind*, *Absent*) as factors (we refer to the masked and unmasked fields as "blind" and "sighted" respectively in this and all subsequent analyses, to reflect their relationship to field deficits in hemianopia). This analysis revealed a statistically significant main effect of Mask Type [$F(2.03,56.71)=15.81$, $p<.001$, $\eta_p^2=.36$], and Target Position [$F(2,56)=27.81$, $p<.001$, $\eta_p^2=.50$], and a statistically significant interaction between Mask Type and Target Position [$F(2.61,73.04)=4.54$, $p=.01$, $\eta_p^2=.14$]. Similar analysis of accuracy data revealed a significant main effect of Mask Type [$F(3,84)=6.71$, $p<.001$, $\eta_p^2=.19$], Target Position [$F(2,56)=38.06$ $p<0.001$, $\eta_p^2=.58$], and a significant interaction between Mask Type and Target Position [$F(6,168)=2.16$, $p=0.049$, $\eta_p^2=.07$]. As is clear from Figure 2, these results indicate 1) an improvement in search performance with increasing blind-field information (a reduction in response time and an increase in accuracy) 2) better performance for present, sighted-field targets compared to blind-field and absent targets, but these differences diminish as more information is added to the blind field.

Table1. Number of fixations per trial in total, as well as, when successive fixations on the same face were excluded.

	Number of fixations per trial	
Mask Type	Total	After removal of successive fixations on the same face
Blank	22	7
Dot	20	9
Filtered	15	9
Unmodified	13	8

Number of Fixations. There was a strong positive correlation between RT and number of fixations per trial [*r*=.945, *n*=348, *p*<.001]. Fixations during search fall into two general categories: those that target, or attempt to target, a new object for inspection (between-object saccades), and those that move around within the already-fixated object (within-object saccades). In masked conditions, we expected more within-object saccades because fixations need to specifically target the masked side of the face to obtain an unobscured view of the emotional expression. Table 1 shows the total number of fixations as well as the number of fixations that remain after repeated sequences of fixations on the same face (within-object saccades) have been removed. It is clear from the table that an increased number of fixations in masked conditions occurs mostly because of these successive fixations. When we exclude these successive fixations from the analysis, and include only fixations that moved between faces or between faces and areas of blank screen, the number of the remaining fixations between different mask conditions are roughly similar. These between-object saccades are more diagnostic of search strategy, so we have isolated these in all further analysis by removing within-object saccades.

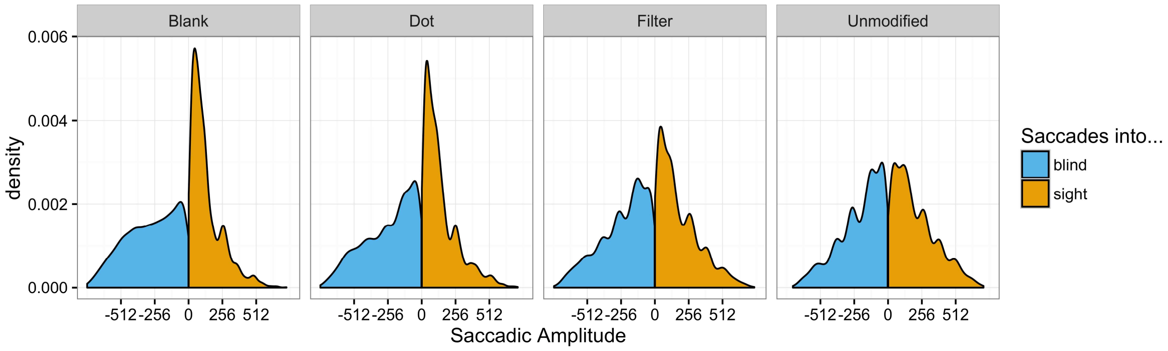

Figure 3. The graph depicts saccade amplitude in the four mask conditions. The length of the *x*-axis on each side of the centre is the screen width. The peaks and notches in the distribution, most noticeable in the *Unmodified* and *Filter* conditions, line up with the regular horizontal spacing of the target items. Relatively more short saccades occur in the sighted than in the blind field.

Saccade Amplitude. Between-object saccades on target-absent trials were subdivided into two categories: saccades directed towards the Sighted and towards the Blind Side. These two categories were defined using a 90° wedge to the left or right of current fixation. Saccadic amplitudes were first log transformed because the data were highly skewed and then the mean saccadic amplitudes were analysed by a 2x4 repeated measures ANOVA with Saccade Direction (*Sighted*, *Blind*) and Mask Type (*Blank*, *Dot*, *Filtered*, *Unmodified*) as factors. This revealed a significant main effect of Saccade Direction [$F(1,28)=42.6$, $p<.001$, $\eta_p^2=.60$], and Mask Type [$F(1.41, 39.43)=4.26$, $p=.03$, $\eta_p^2=.13$], and a significant interaction between Saccade direction and Mask Type [$F(1.91,53.56)=11.94$, $p<0.001$, $\eta_p^2=0.30$]. As can be seen in Figure 3, there was no significant difference in saccadic amplitude between the saccades made into the *Sighted* and *Blind* side [$p=.87$] in the *Unmodified* condition. However in the other three mask conditions saccades were shorter when made towards the *Sighted* compared to the *Blind* side [all p values $<.002$].

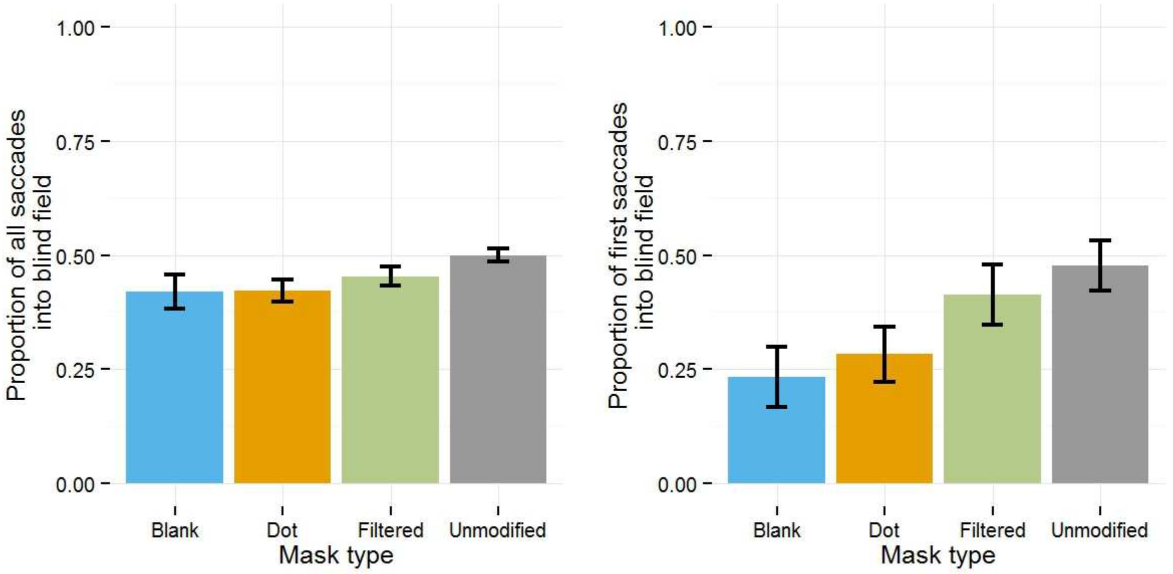

Figure 4. Proportion of all (left panel) and first (right panel) saccades towards the Blind field in the four mask conditions (*Blank*, *Dot*, *Filtered*, *Unmodified*), showing a gradual increase of saccades towards the Blind side as more information becomes available.

Proportion of saccades into the blind field. As a measure of directional bias, we examined the mean proportion of all saccades executed towards the blind field, as well as the proportion of trials on which the first saccade was made into the Blind field. These two measures were first arcsine transformed and then analysed using a one-way ANOVA with a Mask Type (*Blank*, *Dot*, *Filtered*, *Unmodified*) as the independent variable (see Figure 4). We only analysed target absent trials. The assumption of homogeneity of variance was violated; therefore, the Welch F ratio is reported. The statistically significant difference [F(3,59.78)=9.01, p=.002] was further examined using Tukey post-hoc tests. The proportion of all saccades made into the blind field was significantly smaller in the *Blank* [M=.44, SD=0.11, p=.001], *Dot* [M=.42, SD=.07, p<.001], and *Filtered* [M=.47, SD=.06, p=.05] conditions compared to *Unmodified* [M=.52, SD=.04].There was no significant difference between *Blank* and *Dot* [p=1.00] and between *Dot* and *Filtered* [p=.40] conditions.

For the analysis of first saccades only [F(3,112)=13.46, p<.001] the proportion of first saccades made into the Blind field was significantly smaller in the *Blank* [M= .24, SD= .19, p<.001] and *Dot* [M=.29, SD=.17, p<.001] compared to *Unmodified* [M=.51, SD=.17] conditions, and in the *Dot* compared to *Filtered* condition [M=.44, SD= .18, p=.02]. There was no significant difference between *Blank* and *Dot* [p=.71], and between *Filtered* and *Unmodified* conditions [p=.47].

Discussion

Removing stimulus information from one visual field slowed search, due mostly to an increased number of fixations directed successively to the same face. The loss of bottom-up information changes the saccadic behaviour both qualitatively and quantitatively, as seen in the increased amplitude and decreased proportion of blind-field saccades. However, this did not translate to a larger number of between-object saccades needed to find the target.

In general there was a monotonic relationship between saccade behaviour and amount of information loss. That said, the dot and blind conditions were roughly similar, suggesting that stimulus position markers alone, or at least the ones used here, do not significantly affect saccade behaviour relative to no information. One possible explanation is that search items in this experiment were constrained to a limited number of positions, limiting the value of position markers. However, in Figure 3 the peaks and notches in the distribution of amplitudes particularly visible on the sighted field side of each plot represent the proportion of saccades directed to the six possible stimulus locations on the horizontal meridian (three to the left and three to the right of central fixation). These peaks and notches are visible on the blind field side of each plot but become diffused with less information; with no information in the blind field (the "blank" condition) there are no notches, suggesting participants are not preferentially directing saccades to known stimulus positions when the stimuli are not present. The dot condition produces a nearly-smooth distribution, suggesting participants are not directing many saccades to the dots, perhaps because the dots not match the target template.

The effect of condition was significant for blind-field and absent targets, but not sighted, suggesting participants tend to search the sighted field first and then the blind field. This tendency is borne out in large proportion of first saccades executed towards the sighted field. This behaviour, at first glance, may seem counter-productive because it decreases the visible area overall. However, it is not clear if participants would have performed the search task better had they searched the blind field earlier. Given that our participants made about eight between-object saccades per trial in the unmodified condition, they seemed to be inspecting nearly all the search items before making a response. This indicates participants were engaged in an effortful, serial search which may not be facilitated by exploring the blind field first, because both fields needed to be explored in any case. To explicitly test this hypothesis, in the second experiment we shift the fixation point at the beginning of each trial from the centre of the screen to the blind field. If searching the blind field early in the trial is an optimal strategy to apply overall, our manipulation should improve search performance (that is, there will be a significant main effect of search start position). Alternatively, if the optimal strategy is target-position dependent, the search times should increase with the target positioned in the sighted field (because the eyes start search further from the target), but this effect will be negated by better search performance when the target is positioned in the blind field (because the eyes start search closer to the target).

Experiment 2

Method

Participants. Twenty-five participants (females=13; age range =19-32; mean age=22.45 ± 2.71) completed the experiment. All reported normal or corrected-to-normal vision. A different set of participants was recruited for each experiment to eliminate any learning/practice effect.

Materials For simplicity, we decided to include only the *Blank* and *Unmodified* conditions in this experiment. In each of these two conditions the fixation point was either positioned in the centre of the screen (same as in Experiment 1) or shifted into the Blind field (five degrees from the right edge of the screen in Right Mask on right and five degrees from the left edge of the screen in the Left Mask condition) to simulate a situation where participants make large eye-movements into the damaged side at the start of the trial (See Figure 5 for an exemplary stimulus set). Thus together participants were tested under six experimental conditions: two Mask Types (*Blank*, *Unmodified*), two Mask Sides (*Left*, *Right*), and two Fixation cross positions (*Central*, *Blindside*), the order of the blocks being randomised. Otherwise the materials, procedure and apparatus were the same as in Experiment 1.

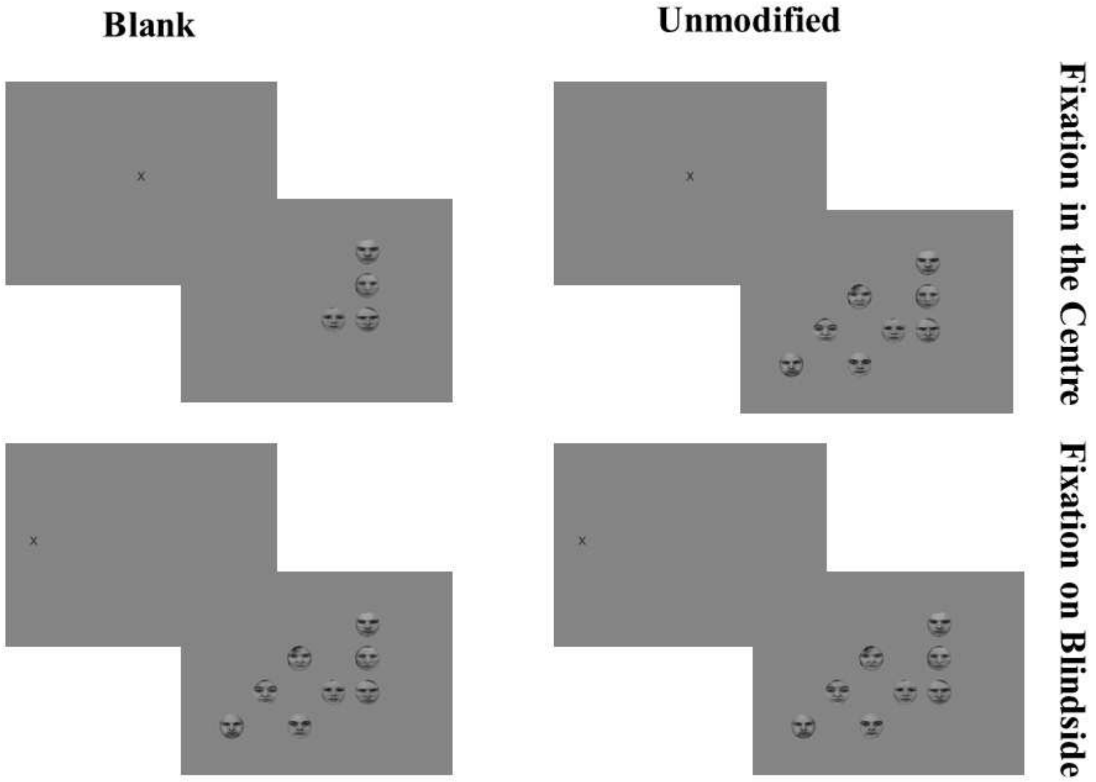

Figure 5. Schematic representation of the four (left) mask conditions showing initial position of the fixation point and example stimuli at the start of a trial.

Results

Reaction time and accuracy. Median reaction time on correct trials was calculated for each participant and was analysed using a 2x2 repeated measures ANOVA with Target Position (*Sighted*, *Blind*) and Fixation cross location (*Central*, *Blindside*) as factors. Although all the data are shown in Figure 6, we included only target present trials in the blank condition in our analysis as these were the key trials to assess our prediction that target position will mediate the effect of where search begins. Importantly, this analysis revealed no significant effect of Fixation Cross Position [$F(1,24)=.21$, $p=.65$, $\eta_p^2=.01$]. There was a significant effect of Target Position [$F(1,24)=10.23$, $p=.004$, $\eta_p^2=.30$] and significant interaction between Fixation Cross Position and Target Position

[F(1,24)=24.97, p<.001, η_p^2=.51]. The interaction implies that the benefits to some targets are gained at the expense of others, with no net benefit to starting search in the blind field.

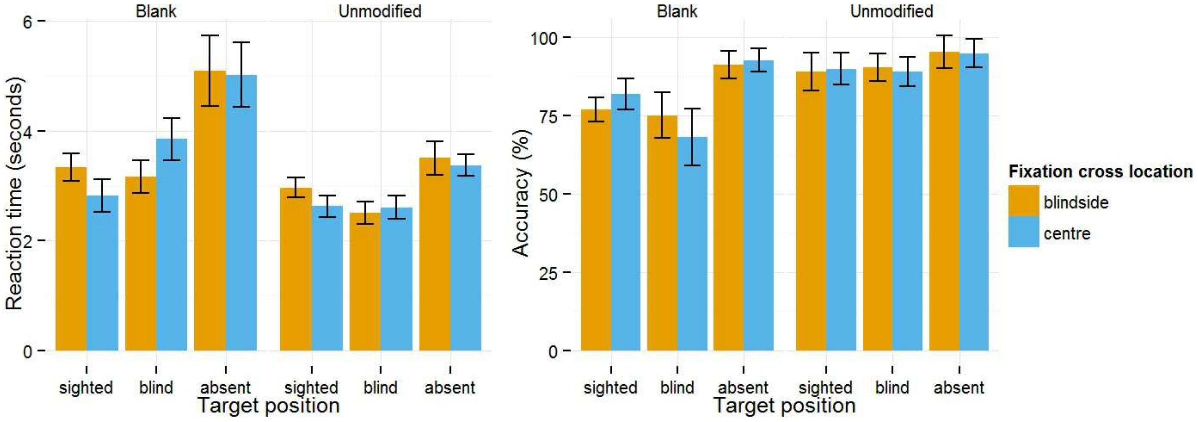

Figure 6. The bar graphs show the means of subject median Reaction times (left panel) and means of accuracy (right panel) in the *Blank* and *Unmodified* conditions split by Target Position and Fixation cross location.

The same analysis as above was applied to percentage correct (Figure 6, right panel). This analysis again revealed no significant effect of Fixation Cross Position [F(1,24)=.45, p=.51, η_p^2=.02], but a significant effect of Target Position [F(1,24)=5.34, p=.03, η_p^2=.18] and significant interaction between Fixation Cross Position and Target Position [F(1,24)=5.25, p=.03, η_p^2=.18]. The similar direction of the interaction of Target and Fixation Cross Position in the RT and accuracy data suggests that the interaction in RT data was not simply due to a speed-accuracy trade-off.

Discussion

We speculated that in our difficult search task, exploring the blind field early in the trial may facilitate search only when the target is in the blind field. Results of

Experiment 2 are in line with this hypothesis. There was no overall benefit of starting the search deep in the blind field. Crucially, this was because of a cross-over interaction of fixation cross location with target position: Placing the fixation cross deeper in the blind field increased search times when the target was positioned in the sighted field (because fixation was further from the target), and decreased search times when the target was positioned in the blind field (because fixation was closer to the target). Together these data demonstrate that making large eye-movements into the blind field is not a universally optimal search strategy. Finding the emotional face among neutral ones was a relatively hard task and required scanning each face individually in order to find the target. Thus a tendency to search the sighted field first cannot be characterised as sub-optimal, but may reflect a (rational) preference to perform small saccades and start from the information already available.

The first two experiments have established that participants are indeed biased to search the sighted field first, and further demonstrate that this strategy does not, under these particular conditions, have negative consequences for search. If, however, the targets were easy to see such that the search would be classified as a pop-out, (Treisman & Gelade, 1984), then there does exist a strategy that will clearly lead to faster target detection, namely: first assess from the centre whether the target is present, and if the target cannot be detected, make a large eye movement into the blind field. If the target were in the sighted field it would be easily detected from the center. Therefore, any eye movements into the sighted field during easy (parallel) search are superfluous and will reveal no new information.

Having established that participants have a preference to search the sighted field first in the first two experiments, the goal of the next two experiments is to ascertain whether participants can adjust this tendency in response to changes in search difficulty. To accomplish this, we shift to using search arrays of line segments rather than faces. The target is a line segment tilted 45 degrees, and difficulty is manipulated by varying the heterogeneity of the orientation of the distractor line segments. Arrays of line segments not only afford parametric variation of search difficulty, but also allow us to generalize our conclusions from search of faces to a new stimulus type[ii].

Experiment 3

In the third experiment we vary the difficulty of the search from very easy to very hard, to examine whether participants change their search strategy in response to increasing difficulty. When the search is difficult it should not matter whether participants start their search in the sighted or blind field, because they have to inspect the whole display closely (similarly to Experiments 1 and 2) in order to find the target (or indicate its absence). However, under conditions where a target is easy to spot in the periphery, and the target is not immediately visible in the sighted field, it would clearly be inefficient to then move the eyes into the sighted field. Under these conditions, participants *should* move their eyes to the blind field.

Method

Participants. Twenty-two participants (females=16; age range =20-33; mean age=24.77 ±3.28) completed the experiment. One participant was excluded from further analysis because her accuracy rate was at chance on the target present trials in the hardest condition (leaving no reaction times to analyse in this condition).

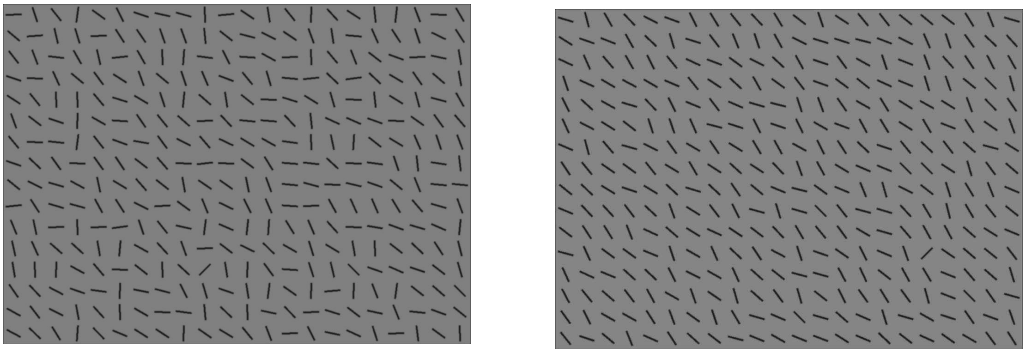

Figure 7. Example line segments: left panel represents the stimuli when the target (a line tilted 45˚ to the right) was difficult to find and right panel when the target was easy to find.

Materials. The stimuli consisted of 100 pre-generated arrays of line segments. Each line was 1.2cm (1.6°) 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 100 images, 50 were target present and 50 target absent. We introduced five 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 106° (range of possible distractor angles from the mean orientation) was the hardest condition and the range of 62° was the easiest condition (see Figure 7 for example stimuli). Difficulty increased incrementally and included 10 stimuli of each difficulty (106, 90, 78, 69, 62)° in both target present and absent conditions. The target was present 25 times on the left and 25 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).

Each participant was tested under 20 experimental conditions: two Mask Types (*Blank*, *Unmodified*) and two Mask Sides (*Left*, *Right*). The same set of line segment stimuli was presented in the four conditions (in random order). Participants were informed that the target was a line tilted 45 degrees to the right and they were asked to indicate (by pressing a respective button on a keyboard) whether it was present or absent. They were also given 20 practice trials. Otherwise the procedure and apparatus were exactly the same as in Experiments 1 and 2.

Results

Reaction time and accuracy. Because search difficulty is a continuous factor (based on the distribution of distractor angles) we used multiple regression to predict Reaction Time from three factors: Search Difficulty, Mask Type, and Target Position. The analysis showed that Mask Type [*Beta*=.32, *t*(629)=11.11, *p*<.001], Target Position [*Beta*=.59, *t*(629)=20.40, *p*<.001] and Search Difficulty [*Beta*=.15, *t*(629)=5.16, *p*<.001] significantly predicted RT [*F*(3,626)=188.66, *p*<.001, R^2=.48]. The same analysis on accuracy also showed significant effects of Mask Type [*Beta*=.34, *t*(629)=9.83, *p*<.001], Target Position [*Beta*=.33, *t*(629)=9.68, *p*<.001] and Search Difficulty [*Beta*=.22, *t*(629)=6.54, *p*<.001] on accuracy [*F*(3,626)=77.66, *p*<.001, R^2=.27]. These results are consistent with the previous two experiments and also demonstrate that our Search Difficulty manipulation was effective. Results are plotted in Figure 8.

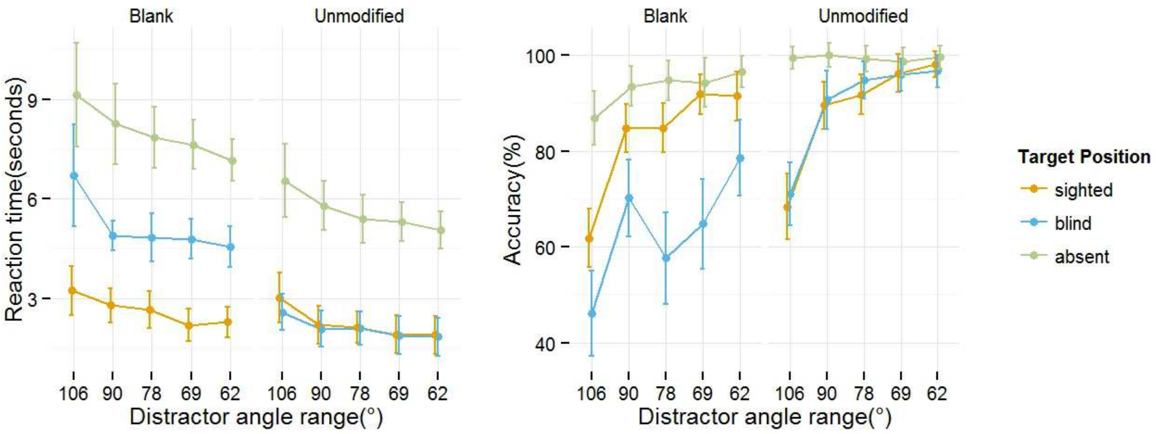

Figure 8. Median reaction time (left panel) and mean accuracy (right panel) for the two Mask Types split by Target Position and Distractor angle range.

Proportion of saccades directed into the blind field. The same multiple regression as above was run with the proportion of saccades directed into the blind field (arcsine transformed prior to statistical analysis) as the dependent variable, with only target absent trials included in the analysis. Mask Type [$Beta$=.59, t(209)=10.49, p<.001] but not Search Difficulty [$Beta$=.001, t(209)=.009, p=.993] were significant [F(2,207)=55.06, p<.001, R^2=.35]. Similarly, for the proportion of first saccades directed into the blind field, Mask Type [$Beta$=.26, t(209)=3.83, p<.001] but not Search Difficulty [$Beta$=.004, t(209)=.04, p=.53] were significant [F(2,207)=7.53, p=.001, R^2=.07]. This result is shown in Figure 9.

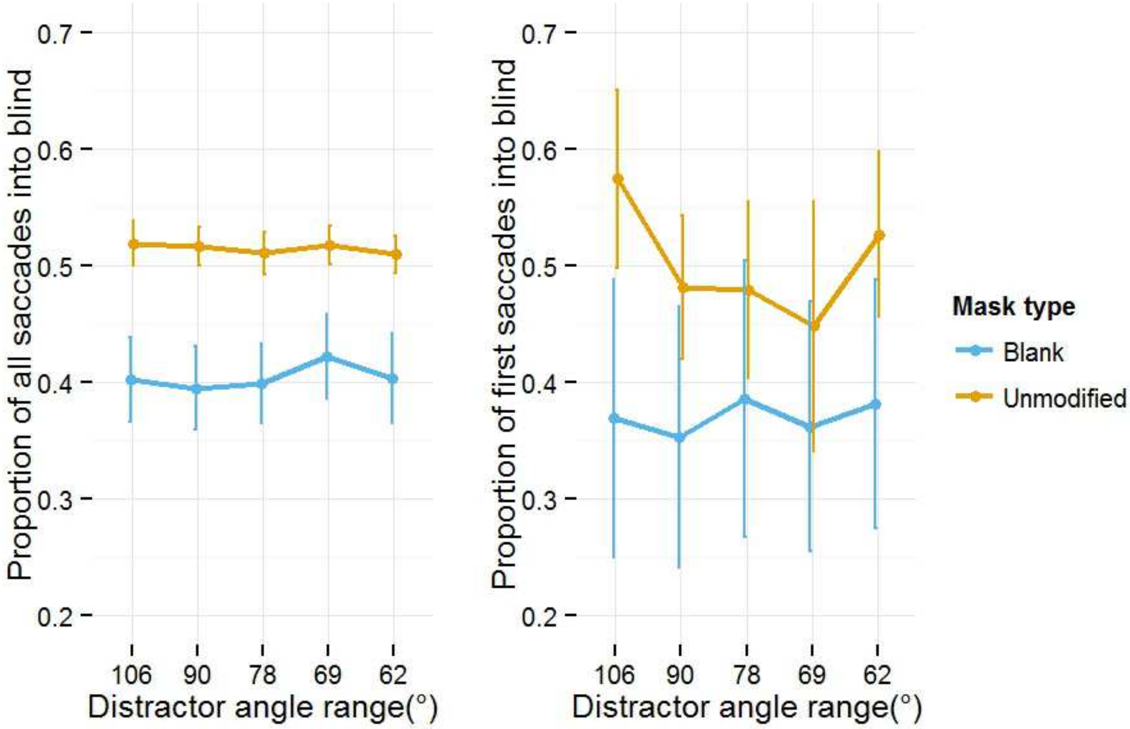

Figure 9. Proportion of all (left panel) and first (right panel) saccades towards the blind field in the two mask conditions (*Blank*, *Unmodified*) split by five search difficulty levels (distractor angle range). The data include only target absent trials. As the search becomes easier more first saccades should be directed towards the blind field (on masked trials). Our participants however do not modulate their saccadic

behaviour and regardless of search difficulty direct more first and a larger proportion of all saccades into the sighted field.

Discussion

The reaction time and accuracy results confirm that our search difficulty manipulation was effective. Nonetheless, participants preferred to saccade first, and more often, into the sighted as opposed to the blind field to a similar extent across the five difficulty levels. When the target was easy to spot in the periphery, and it was not initially visible in the sighted field, participants should have immediately moved their eyes deep into the blind field to search for the target. Yet participants were consistently biased towards the sighted field, irrespective of the ease of target detection. Had participants been able to implement a strategy of searching the blind field when the target was not immediately apparent on easy trials, we would have also seen a decrease in the performance difference between blind- and sighted-field targets with decreasing search difficulty. Instead, this difference is consistently large across search difficulty.

The variability of the distractors signals the visibility of the target, so this information is equivalently available across the search array, and is available as soon as the search array appears. Nonetheless, the results suggest participants fail to change search strategy with target visibility. This result is inconsistent with previous models of search suggesting participants can use information from the search array as a whole to select fixations during search that maximize the chances of target detection (Najemnik & Geisler, 2005) However, in this experiment we randomly interleaved trials of five different difficulty levels. The more subtle variation in difficulty from trial to trial may cause participants to employ one uniform search strategy that matches the most difficult distractor condition. Therefore in the fourth experiment we only test participants under two conditions: parallel (pop-out) and serial. If the search is easy (it is a pop-out) and the target is initially not visible in the sighted field, the optimal strategy is to make the first saccade deep into the blind field. In the easy condition, participants should be able to tell without making any eye movements (if it is in the sighted field) or with one eye-movement (if it is in the blind field) whether the target is present or absent. Therefore the reaction time difference between target present in the blind and in the sighted field should be about the time it takes to execute one eye movement (about 300ms).

Experiment 4

Method

Participants. Twenty-one participants (females=18; age range =19-36; mean age=24.36 ± 2.83) completed the experiment. One participant was excluded from further analysis due to a lack of correct responses on the target present trials in the blind field serial search.

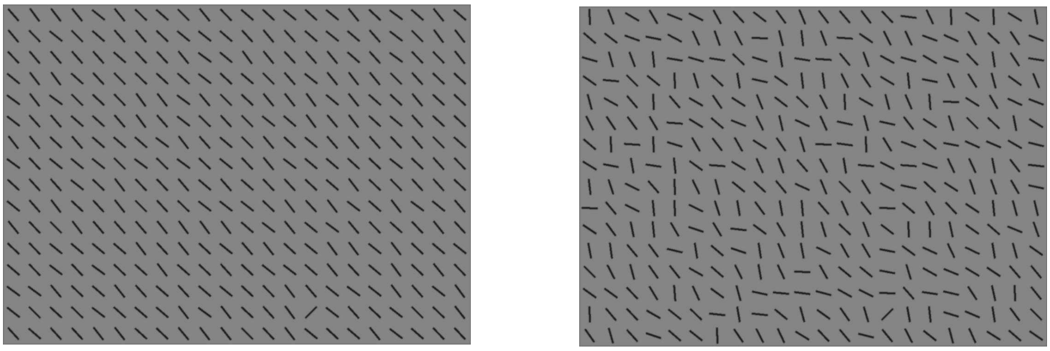

Figure 9. Example line segment stimuli: left panel represents the stimuli in parallel search condition and right panel serial search condition.

The line segment stimuli were generated in the same way as in Experiment 3, except there were only forty pre-generated line segment images. We introduced two levels of search difficulty where distractor angle range of 90° represented serial search, and the distractor angle range of 9° represented parallel search (See Figure 9 for example stimuli). Of the 40 images, 20 were target present (10 parallel 10 serial) and 20 target absent. Otherwise the method was exactly the same as in Experiment 3.

Results

Reaction time and accuracy. For simplicity, target absent trials and the unmodified condition were not included in the analysis, but the results are shown in full in Figure 10. A 2x2 repeated measures ANOVA on RT with Target Position (*Sighted*, *Blind*) and Search type (*Parallel*, *Serial*) as factors produced a significant effect of both Target Position [$F(1,19)=15.58$, $p=.001$, $\eta_p^2=.45$], and Search Type [$F(1,19)=17.56$, $p<.001$, $\eta_p^2=.48$]. The interaction between Target Position and Search Type was marginal [$F(1,19)=4.32$, $p=.052$, $\eta_p^2=.19$]. From Figure 10, it can be seen that the RT difference between sighted and blind field targets was smaller for parallel than for serial search.

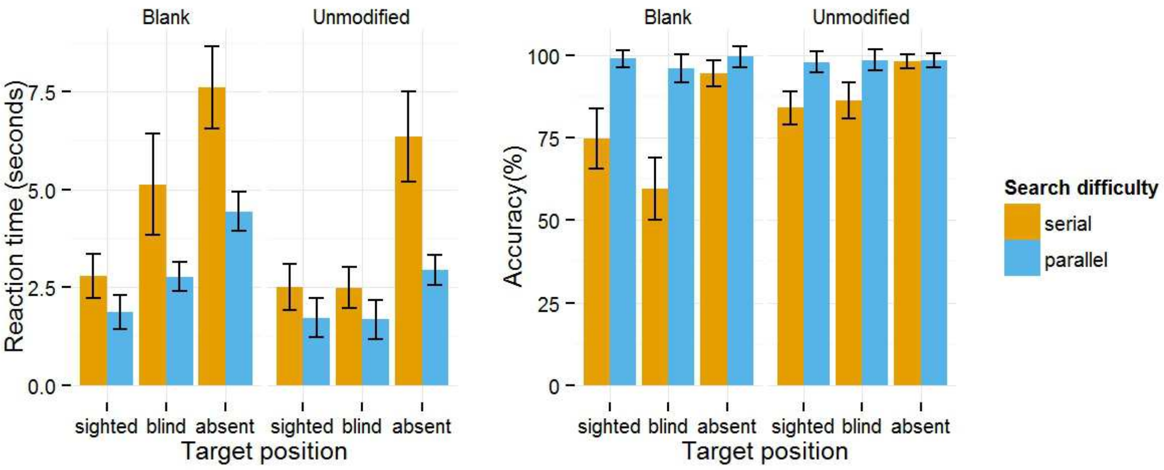

Figure 10. The bar graphs show the means of subject median reaction times (left panel) and mean accuracy (right panel) in the *Blank* and *Unmodified* conditions split by Target Position and Search Difficulty.

A similar analysis of the accuracy data revealed a significant main effect of both Target Position [$F(1,19)=9.70$, $p<.001$, $\eta_p^2=.73$], and Search Type [$F(1,19)=49.98$, $p<.001$, η_p^2

=.73] and an interaction between Target Position and Search Type [$F(1,19)=4.56$, $p=.046$, $\eta_p^2=.19$]

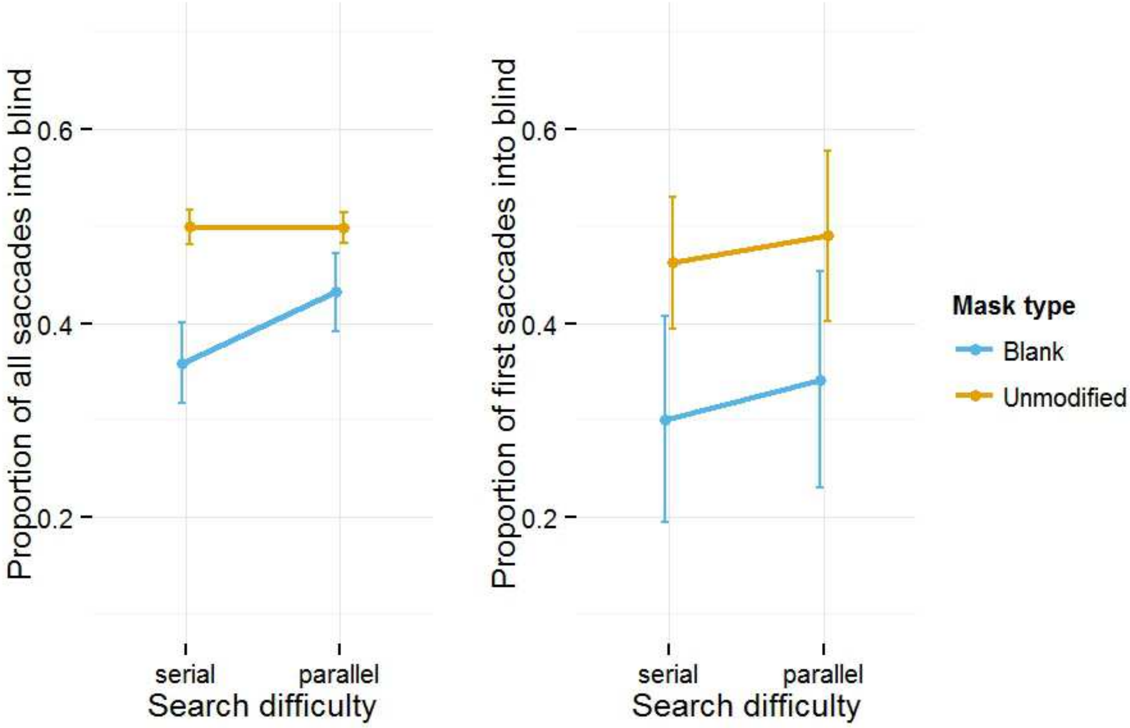

Figure 11. Proportion of all (left panel) and first (right panel) saccades towards the blind field in the two mask conditions (*Blank*, *Unmodified*) split by search difficulty. The data include only target absent trials, so the optimal first saccade during parallel search would be directed towards the blind field (on masked trials) 100% of the time. Instead, the first saccade is directed to the blind field about 34% of the time.

Proportion of saccades directed into the blind field. Because we are interested in assessing search strategies when the target is not initially detected in the sighted field, we excluded the unmodified condition and target present trials from analysis. Overall, a bias towards the sighted field was present in the masked condition, replicating the previous experiment. A paired t-test confirmed that a larger proportion of saccades were directed to the blind field during parallel than during serial search [$t(19)=5.81$, $p<.001$], see Figure 11, left panel.

The more important analysis is whether participants directed their *first* saccade during search into the blind field, as this represents an efficient strategy particularly in the parallel search condition. A paired t-test comparing the proportion of first saccades directed towards the blind field for serial and parallel search found that there was no significant difference between the two conditions [*t*(19)=.82, *p*=.42]. This result is surprising, and confirms the results of the previous experiment: on trials in which the target should pop out, and it is not immediately apparent in the search array, participants *should* direct their first eye movements into the blind field on 100% of trials. What we observe, however, is that the first eye movement of search is directed towards the blind field on only about 34% of trials.

Although overall participants preferred to saccade first to the sighted side, Figure 12 illustrates that four out of 20 participants did appear to alter their strategy and increased their number of saccades made to the blind field when the search became easy. Three of these four participants managed to reverse the sighted-field bias and saccade towards the blind field on more than half of trials – still falling well short of 100%, but nonetheless these participants could be characterised as having adapted search strategies appropriately to the change in difficulty. However, fourteen participants did not modify their strategy or only did so slightly, and two participants exhibited a pattern in the opposite to the optimal direction. Results of additional analysis of proportion data (proportion of all saccades and proportion of first saccades in the blind field) involving a 2x2 ANOVA (with Mask Type and Search Difficulty as factors) are reported in the supplementary materials.

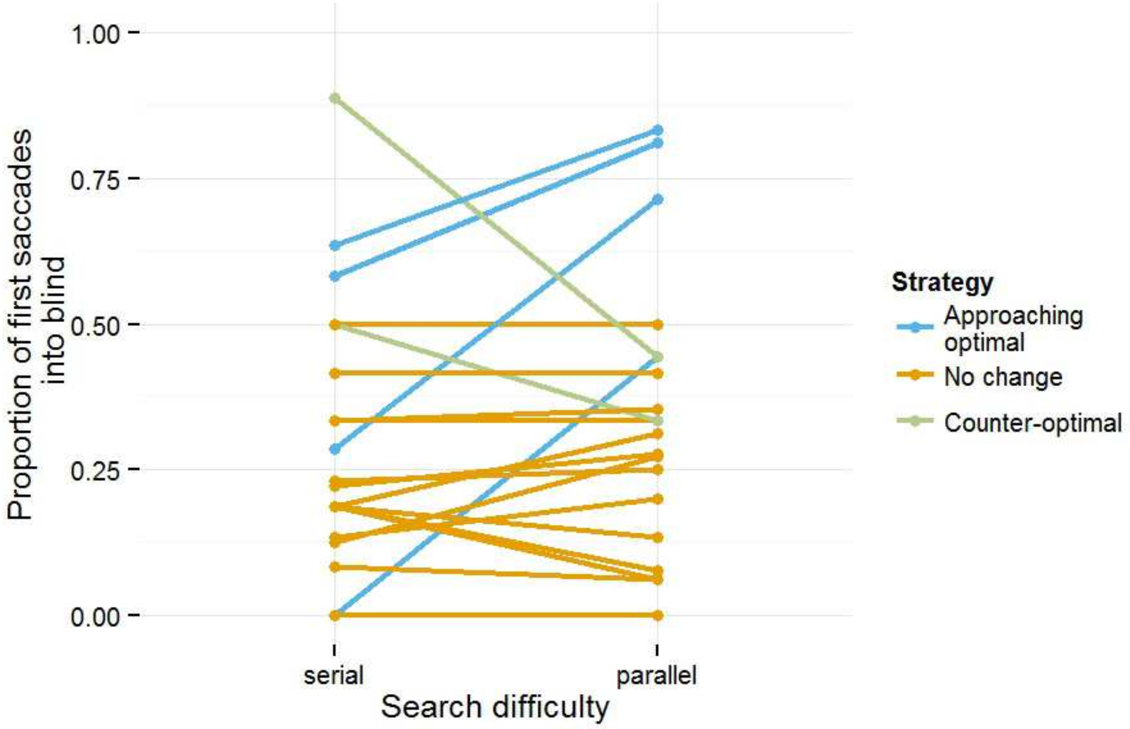

Figure 11. Proportion of first saccades towards the Blind in the *Blank* condition split by Search Difficulty for each individual subject. The blue line represents participants who approached the optimal strategy by increasing the number of first saccades directed to the blind field in response to a pop-out target. Orange lines represent participants who did not change their strategy (or only did so slightly), and green line represents participants who shifted their strategy in the opposite to the expected direction.

Discussion

Participants took significantly longer to detect the target when it was in the blind field compared to the sighted field in both the serial and parallel search conditions. These results, particularly in the parallel search condition, suggest our participants did not use an optimal search strategy of making one large saccade towards the blind field when the target was clearly not present in the sighted field. The eye movement data confirm these conclusions. Although overall participants made more saccades into the blind field in the parallel compared to serial conditions, the vast majority of first saccades continued to be directed into the sighted field. Notably, there were some individual differences between our participants. Four out of twenty changed their strategy as a function of search difficulty by moving their eyes more into the blind field in the condition where the target was highly visible. Yet, none of our participants was optimal in the strictest sense, which would entail all first saccades on the target absent trials being directed towards the blind field. Thus overall this experiment highlights that our participants were consistently biased towards the sighted field even when blind-field saccades would be of clear and direct benefit to search efficiency.

General Discussion

In all four experiments participants were consistently biased towards the visible part of their visual field. In the context of Experiment 1 and 2, this sighted-field bias neither helped nor harmed search performance; but crucially, Experiment 3 and 4 demonstrated that participants continued to direct eye movements into the sighted field even when these eye movements gained them very little new information and impeded search performance.

The proportion of saccades directed towards the blind field increased with the amount of information available (Experiment 1). In the context of visual search models suggesting saccades are directed to locations that maximize information gain (Najemnik & Geisler, 2005), one might have expected complete removal of information to increase saccades towards that region of space, as a saccade in that direction will produce the most information. Nonetheless, it is also well known that the eyes tend to be directed towards salient information (Itti & Koch, 2000), and that directing eye movements towards empty locations is slower and more error-prone than making eye movements towards visible targets (Hallet, 1978; Hallet & Adams, 1980). Our results suggest the tendency to saccade towards salience wins out over strategic saccades that maximize information gain. Similarly, Tant and colleagues suggested that hyperactivation of the intact hemisphere causes a bias towards the sighted field in hemianopic patients in grey scale judgement task (Tant, Kuks, Kooijman, Cornelissen, & Brouwer, 2002b; but see Barton and Black (1998) for evidence of contralateral bias in a line bisection task). A similar mechanism could also be at work, to some extent, in simulated hemianopia.

In the context of serial search, it may make sense to search the "easier" space first and if the target is still not found, tackle the more difficult space. Consistent with this, we showed that the effectiveness of making large eye-movements deep into the blind field depended on where and what kind of information was present in both the blind and the sighted field. Shifting the location of initial fixation and thus making the display fully visible at the start of the trial (Experiment 2) did not improve search overall: the target was found faster when it was on the blind side but slower when it was on the sighted side, negating the benefits of starting search on the blind side. There are diverse treatment protocols designed to increase scanning of the blind field in hemianopia (e.g.,; Bolognini, Rasi, Coccia, & Ladavas, 2005; Zihl, 1995), and there is evidence to suggest that those treatments increase allocation of attentional resources towards the blind hemifield (Kerkhoff, Munssinger, & Meier, 1994). However, the strategy of making large saccade into the area associated with field deficit advocated in the literature (Mannan et al., 2010; Pambakian et al., 2004; Zihl, 1981) failed to produce significantly better outcomes than the one spontaneously adopted by our observers. A more effective approach may be to train patients to rapidly adjust their search strategy to the particular visual context. For example, if the patient is looking for a small object in a cluttered environment, searching the sighted field first may be both more comfortable and more effective. However, for a bright, highly visible object, a large eye movement into the blind field is a reasonable strategy. It is also important to consider situations in which contextual information is available (Kasneci et al., 2014; Papageorgiou et al., 2012), as these would comprise most search contexts a patient would encounter in the real world. In these situations, eye movements can be directed to likely target locations, and the effect of strategy and salience will be minimal.

The sighted-field bias persisted across search difficulty, which we manipulated by altering the heterogeneity of the distractors (Experiments 3 and 4). This result was surprising because during search for a pop-out target, participants should have executed a large saccade into the blind field on trials where the target was not immediately detected in the sighted field. Similarly, when participants were given location pointers (Experiment 1) an optimal strategy was to make smaller, more precise saccades to the potential target locations in the blind field instead of the large ones that they made in the blank condition. Yet, our participants failed to integrate the information across the entire visual field, instead neglecting the supplied location pointers and continuing search as if no additional information in the blind field were available. It is only when degraded information (in the filtered condition) became available that our participants started making significantly more saccades to the “blank” part of the display. Thus we conclude that eye movements in our observers are driven largely by bottom-up visual information and these observers do not switch their preferred search strategy under circumstances when it would be beneficial to examine the area corresponding to the field deficit first.

In Experiments 3 and 4, we manipulated target visibility by varying distractor heterogeneity, and this had no effect on search strategies. In this respect, our participants, similarly to Verghese (2012) and Morvan and Maloney’s (2012) participants, failed to spontaneously adopt an optimal search strategy and maximise information gain with each fixation. Healthy observers do not seem to be armed with the sophisticated search mechanism advocated by Najemnik and Geisler (2005, 2008). Our data are also consistent with the findings from modalities in addition to vision, demonstrating that humans fail to modify their behaviour to cope with changes in task difficulty (in memory, target detection, throwing; Clarke & Hunt, 2016).

How can one explain the discrepancies between the Najemnik and Geisler (2005) findings of optimal search and Janssen and Verghese findings of optimal strategy in matching task (2015) and the ones observing essentially idiosyncratic and/or stimulus-driven search such as that observed in Morvan and Maloney's (2012) and our study? There are notable methodological differences between our study and that of Janssen and Verghese (2015) studies that make parallel conclusions difficult. Unlike in our study, their participants' viewing time was constrained to 2 seconds and stimuli disappeared within 300ms of the first eye movement. An optimal strategy was to make just one saccade to the occluded area. Moreover, participants received immediate feedback on the correctness of their responses and thus on the correctness of their saccadic strategy (Janssen & Verghese, 2015). The combination of constrained behaviour choice and direct (immediate) feedback could have supported the adoption of more optimal behaviour in their experiment. It is also potentially quite important that two out of six participants in their study were authors of the study; knowledge about what the optimal behaviour is could certainly make participants more likely to exhibit it. This is also an issue in Najemnik and Geisler (2005) in which the data against which an optimal search model is compared comes from the two authors of the study.

The fact that our participants (and those in other studies) did not spontaneously adopt an optimal strategy has important implications for clinical practice. It could be suggested that patients require specific training to optimize their eye-movements in laboratory and real life search tasks since an optimal strategy does not develop spontaneously. Janssen and Verghese's (2015) study provides a nice example that it may be possible to teach participants an optimal strategy under constrained conditions by providing immediate feedback. It is important to note two differences between our healthy participant data and patient data, however. Firstly, although our participants prefer to explore their sighted field first, as in previous visual search studies of patients with hemianopia (Chedru et al., 1973), patients tend to spend more time overall looking into the side associated with the deficit on a free viewing task (Ishiai et al., 1987). Our participants direct more saccades to the side of the screen opposite to the area associated with the deficit. This could be for a number of reasons. Firstly, it may be that because of the limited time our observers were subjected to the deficit, a consistent search strategy did not develop. Exposing observers to multiple testing sessions and thus providing extensive practice could serve as a way to test this prediction. Second, and similarly, patients may adapt differently (and more efficiently) because they have more at stake. Our participants are aware that their deficit will end with the experiment, but patients would be more motivated to succeed in adapting to a long-term deficit. Third, there may be a particular effect of brain damage over and above the visual deficit that is responsible for the specific eye-movement pattern. Tant and colleagues (2002) also stated that visual deficit is the main but not the only factor that contributes to the abnormal oculomotor behaviour seen in patients. The fourth possibility is that patients move more to the blind field because they possess some residual visual abilities in their damaged field of vision that guide their search more effectively. Since we observed different degrees of search deficit depending on the kind of information preserved in the blanked field we might speculate that presenting healthy participants with a blank screen to simulate field deficit might not be applicable to all hemianopic patients. In support of this interpretation, Tant et al. (2002) showed that for most eye-movements measures (search times, errors, number and duration of fixations) healthy participants with simulated hemianopia were more impaired than patients with hemianopia. They suggested one explanation for this pattern of results was that patients had more time to adapt to their deficit compared to healthy observers. Yet, an alternative explanation would be that healthy participants with simulated hemianopia do not have any residual visual information in their blind side since they were erased by blank space, while at least some patients could rely on spared vision to guide their search.

Similar to other studies that reported on optimality in vision (Janssen & Verghese, 2015) and other modalities (Clarke & Hunt, 2016) we found some individual differences between our participants in that four out of the 20 participants in Experiment 4 adapted their search strategy in response to changing circumstances and started search from the blind field when the search was easy. Zihl (1999), in a study of 70 patients with hemianopia, concluded that the degree to which participants spontaneously compensate for their visual field deficit depends on the extent of their brain injury. We speculate that some variability in the compensatory strategy development or its lack could also be explained by individual differences.

Conclusion

Healthy adults deprived of bottom-up information in half of their visual field tend to preferentially move their eyes towards their sighted field of vision. When search is difficult and requires inspection of individual items serially this bias does not harm search performance. When search is easy, and the target is clearly visible in the periphery, saccades towards the sighted field are superfluous and only serve to slow search. Nonetheless, the bias to preferentially search the sighted field persists even in easy search. These results have important implications both for understanding the processes and strategies involved in visual search, and also for devising effective interventions for patients with visual deficits.

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[i] We recognize that more detailed comparison of target absent vs. present conditions may be relevant to questions about the effect of self-terminating vs. exhaustive search. This is beyond the scope of the current study, but for those interested, detailed results

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are reported in the supplementary data for experiments 1, 2, and 4, including all post-hoc tests.

[ii] In homonymous hemianopia, residual discrimination appears to rely on low spatial frequency visual information (Bannerman et al., 2012; Sahraie et al., 2013). Faces are complex visual stimuli with different information contained at different spatial frequencies, while oriented line segments are far simpler, containing the same orientation information at high and low frequencies. If we filtered the lines using the same procedures as the faces, orientation information would still be present at both high and low spatial frequencies.