An efficient search strategy does not develop spontaneously with repeated exposure to simulated visual deficit.

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**Abstract**

Healthy participants with simulated visual deficit (hemianopia) fail to adopt efficient eye movement strategies when searching for a target object. A possible explanation is that participants are not exposed to the deficit long enough for coping strategies to develop. In the current 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. Participants completed five testing sessions over five consecutive days and received monetary payment for improvements in performance. Participants did improve on the task in terms of reaction time and accuracy, but these improvements were mainly associated with improved peripheral vision rather than a change in search strategy. Participants persisted in directing a large proportion of saccades to the sighted field under conditions where little or no new information about the target location would be gained by doing so. However, more eye movements were directed into the blind field in the first compared to the last session, and this small improvement in strategy may have improved their performance on an object naming task which participants completed before and after training. Add control experiment results here.

Key words:

Visual search, optimality, blindsight, hemianopia

Homonymous hemianopia is a loss of vision in half of the visual field in both eyes following unilateral lesion of the post-chiasmic visual pathway. The visual field loss experienced by patients has a profound impact on patient’s day-to-day functioning and is often associated with difficulties carrying activities of daily living (ADL) 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). Deficits in ADLs are mainly associated with abnormal eye-guidance and visual exploration strategies that hemianopic patients develop over time. Patients with established hemianopia tend to scan the visual world in a more haphazard and disorganised way than healthy controls, with frequent re-fixations and imprecise saccades, showing poorer target detection and longer reaction times (Meienberg, Zangemeister, Rosenberg, Hoyt & Stark, 1981; Zihl, 1995; Zihl, 1999). While viewing naturalistic scenes, patients tend to fixate different spatial regions and make more fixations of shorter duration compared to healthy observers (Ishiai, Furukawa, & Tsukagoshi, 1987; Pambakian, Wooding, Morland, Kennard & Mannan, 2000). Patients also direct more saccades towards their damaged hemifield, with these saccades being of shorter latency and amplitude (Pambakian et al., 2000).

Some patients spontaneously compensate for their visual field loss over time, by adopting more efficient eye movement strategies (Zihl, 1999; Zihl & von Cramon, 1985), however an estimated 60% of patients continue using abnormal visual scanning strategies when searching for a target object (Zihl, 1995). One technique that has been shown to improve patient’s 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 as little as 7 hours of practice (Schuett, 2009), and after only one session of therapy (300 trials) on a real-world task (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; Zihl, 1981).

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 specific search task? 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; Nowakowska, Clarke & Hunt, 2017; Verghese, 2012). The results of these latter studies are more consistent with a stochastic model of eye movements during search, where each eye movement during search is randomly selected from a population of the eye movements participants tend to make from that region of the screen (Clarke, Greene, Chantler & Hunt, 2016; Clarke, Stainer, Tatler & Hunt, in press).

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 or an angry face among neutral faces. 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 with the amount of information available in that field. We also kept the target 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 no new information under these circumstances; indeed, they substantially *decrease* information by shifting the simulated deficit across a larger proportion of the 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 models 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. Therefore, in the current study we investigate whether repeated exposure to a simulated visual field deficit leads to the development of an efficient search strategy. In the main task, participants completed a visual search task every day for five consecutive days under conditions of simulated hemianopia. As in Experiment 4 of our previous study (Nowakowska et al., 2016) participants searched for a line tilted 45 ° to the right hidden amongst distractor lines of varying degree of tilt. Target visibility was manipulated by varying the heterogeneity of the distractor line segment orientations. Participants were rewarded monetarily for improving their search performance from session to session, to encourage them to find strategies to find the target faster.

In the first and last session of the five-day experiment, participants completed two additional tasks: detection and object naming. In the detection task, the same search displays as in the training task were shown, but for only 200ms, which is too brief a presentation time for any useful eye movements to be executed. The aims of the detection task were 1) to confirm that participants were able to detect the target in the periphery on a homogeneous background, without making any eye movements and 2) to measure the extent to which any improvements in search performance over the five sessions could be due to changes in perceptual sensitivity to the target rather than to changes in eye movement strategies. In the object naming task, we simply asked participants to view a series of images, each for four seconds, and name as many objects from each image as they could. The goal of this task was to estimate the extent to which any improvements in performance in the training 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 eye movement strategies improve, we should see increasing efficient search during training, as measured by the proportion of eye movements directed towards the “blind” field. If we do observe increasingly efficient search over the week, we can also measure whether this learning transfers to the object naming task by comparing improvements on this task to the control group’s performance.

**Method**

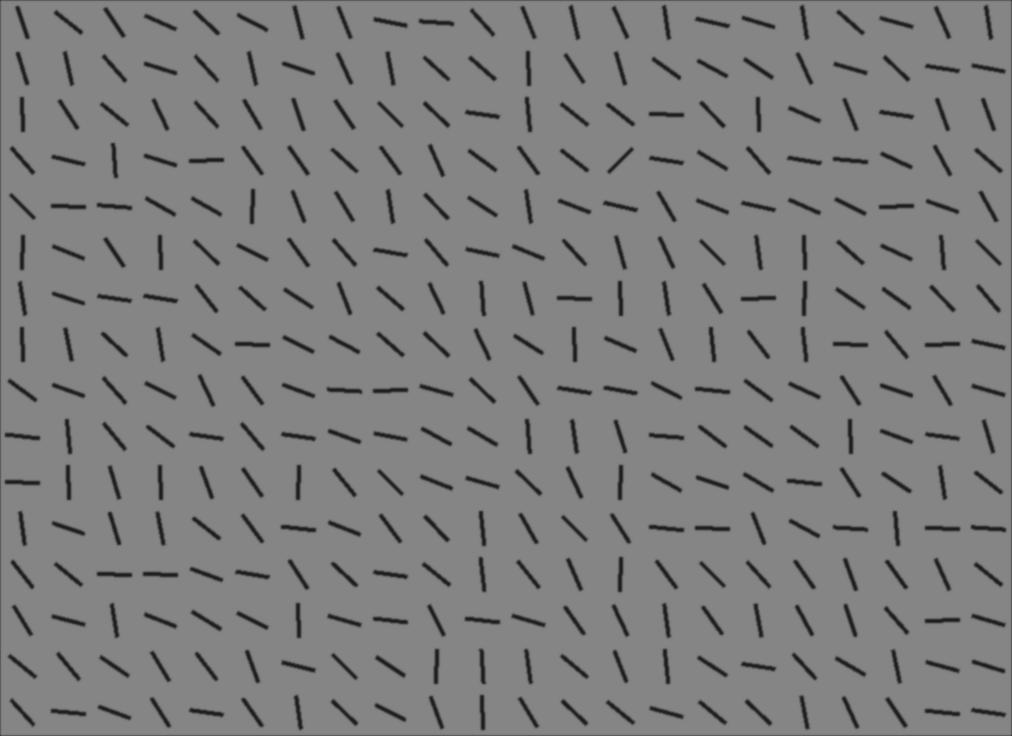
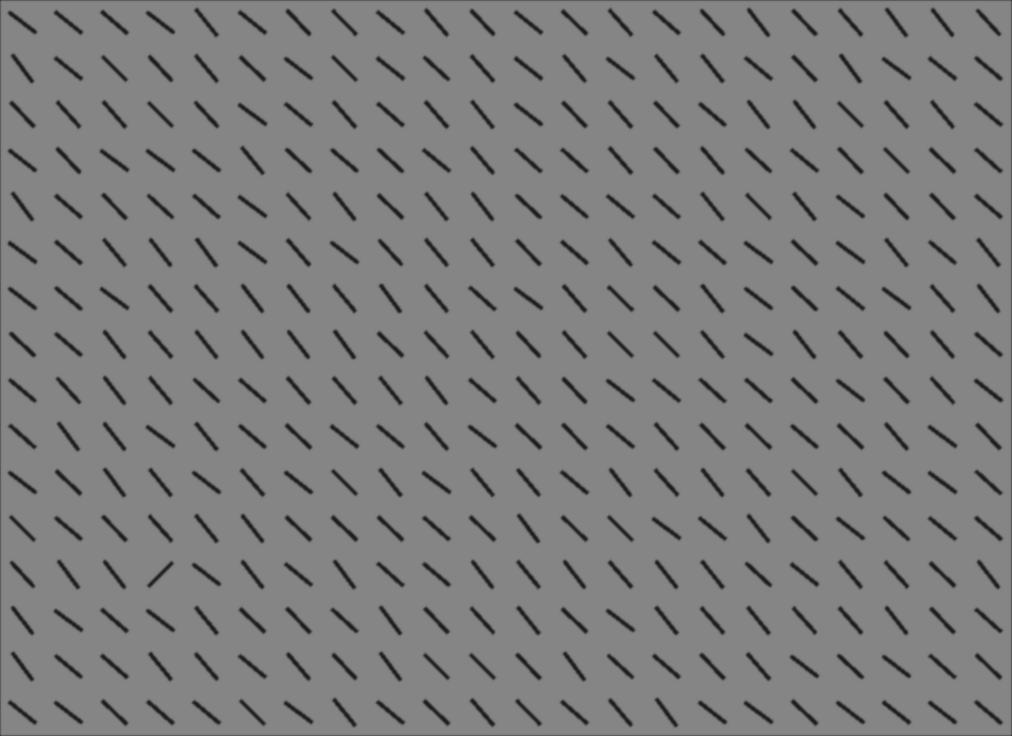
*Participants.* Thirty-four participants (age range =19-36; mean age=22.8 ± 3.99) completed the experiment. Seventeen participants were in the training group (females = 15) and 17 were in the control group (females = 12). All reported normal or corrected-to-normal vision.

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

*Overview of Procedure.* On arrival at the laboratory each participant was asked to read and sign a consent form and was seated alone in a small low-lit room. In the first session, the training 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 Tuesday, Wednesday and Thursday session, participants in this group only did the search task. On Friday they did all three tasks again. The control group completed the object-naming and detection tasks during the first session, and then they completed these two tasks again on Friday. 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 Monday session, the experimenter reminded participants in the training 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 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 Monday session to make sure they could not deliberately under-perform on the first session to make it easier to improve. Thus participants in the training group could be reimbursed a maximum of £40 pounds if they performance improved on every session.

***Search training task***

This task was completed by the training group every day for a work week, starting on Monday and finishing on Friday. Each participant was tested under two experimental conditions: *Simulated Hemianopia (SH) and Unmodified* (control). Under the SH 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 *Unmodified* condition eye movements were sampled 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 (*Unmodified* condition). Block order was randomized in each session. Participants were informed of the condition and underwent a nine-point eye movement calibration sequence before each block of trials.

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*Figure 1*. 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.

The stimuli in each block consisted of 80 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 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 hardest condition and the range of 18° was the easiest condition (see Figure 1 for example stimuli). 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 luminance were matched (17±1 cd/ m²).

Each trial began with 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 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.

***Detection task***

*Stimuli and procedure.*

This task was carried out before the first search training block on Monday and after the last search training block on Friday. The 80 search arrays of line segments we used in this experiment were exactly the same as the ones in the Search Training Task. 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°x3.1°), 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 reaction times in the main task (simulated hemianopia) transfer to other tasks/objects.

*Stimuli and procedure.*

*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 for four 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 voice recorder. For more information on the image set see Clarke et al., 2013). 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 training 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**

Eye movement behaviour in the training task.

To measure search efficiency, we were particularly interested in eye movement behaviour in 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 X depicts the mean horizontal (x) position of the first ten fixations for each participant over the five sessions on the easy search trials when the target was absent. If participants searched the blind side more or earlier with training, there should be a shift in the distribution towards the negative side as the session number increases. It is clear from this figure that there was no such shift: participants distributed their eye movements roughly equally between the blind and sighted sides.

We also examined how search difficulty and simulated hemianopia influenced search performance as measured by accuracy and reaction time.

Accuracy

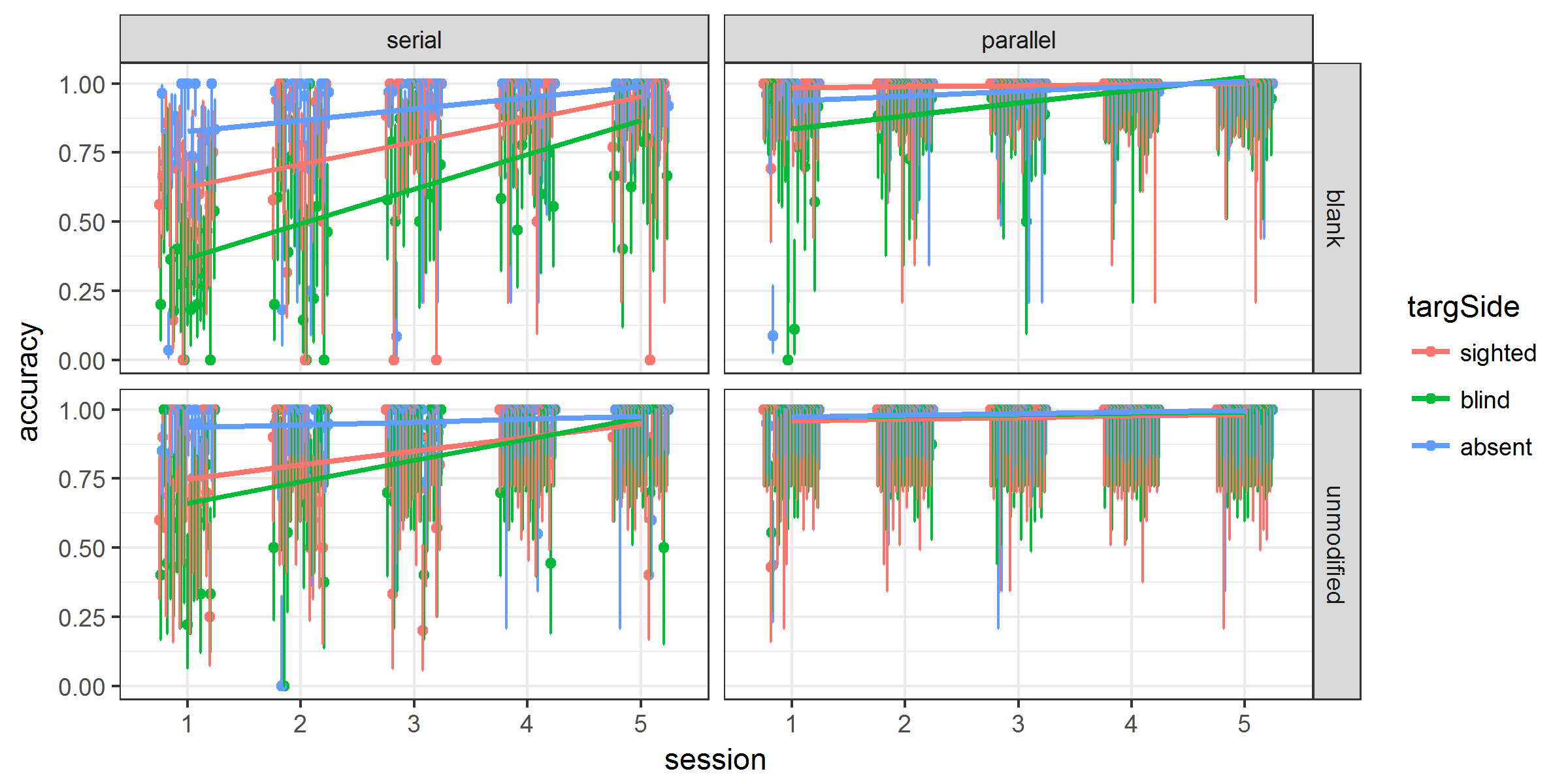


Figure 5. Mean accuracy for the blank and unmodified condition shown for two difficulty levels (serial and parallel) and three target positions (target in the sighted field, blind field and target absent trials) and five consecutive sessions.

A multiple regression was run to predict Accuracy from session, trial type, target side and variability. These variables statistically significantly predicted RT, F (4, 1015) = 94.00, p < .0005, R2 = .27. All four variables added significantly to the prediction, p < .05. As can be seen from Figure 5, accuracy is higher for easier search, improves over the sessions, and is 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 it is not found.

***Reaction Time***

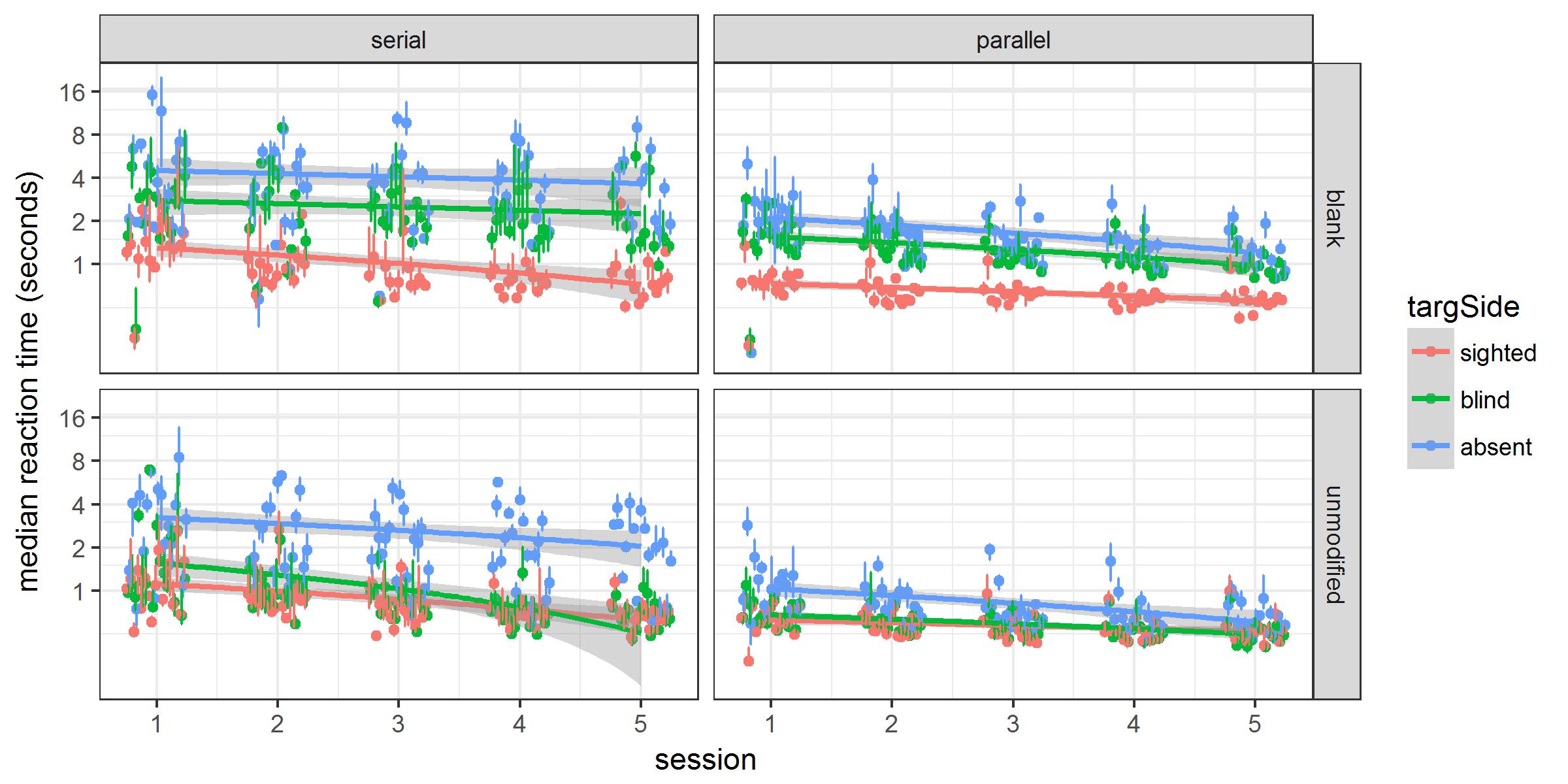


Figure 6. Mean of the median Reaction Times for the blank and unmodified condition shown for two difficulty levels (serial and parallel) and three target positions (target in the sighted field, blind field and target absent trials) and five consecutive sessions.

A multiple regression was run to predict Reaction Time from session, trial type, target side and variability. These variables statistically significantly predicted RT, F (4, 1015) = 154.74, p < .0005, R2 = .577. All four variables added significantly to the prediction, p < .05. As can be seen from Figure 6, RTs are faster for easier search, and they improve over the five sessions. RT is faster when the target is in the sighted field, and the simulated hemianopia slows search.

Eye tracking results

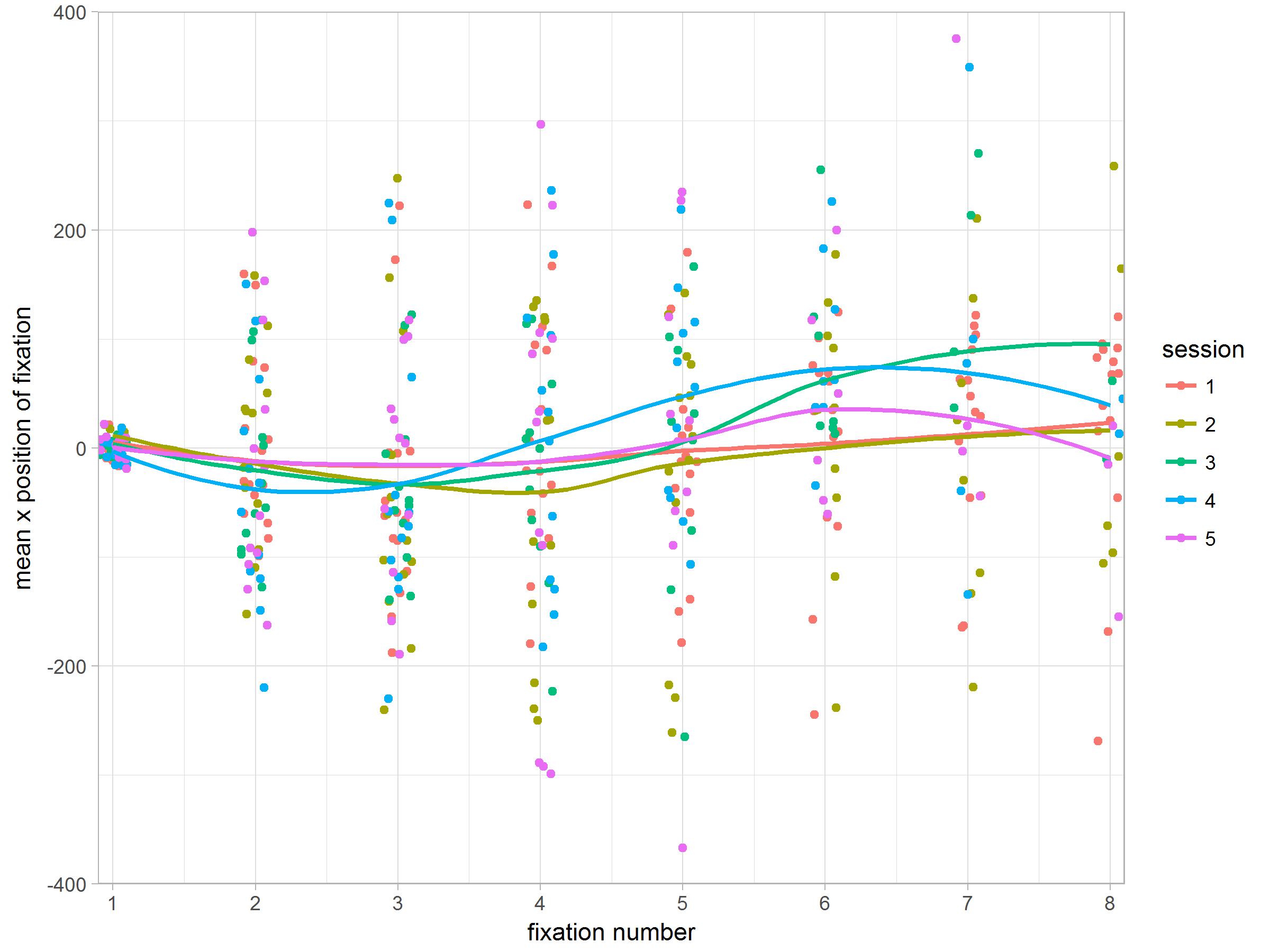
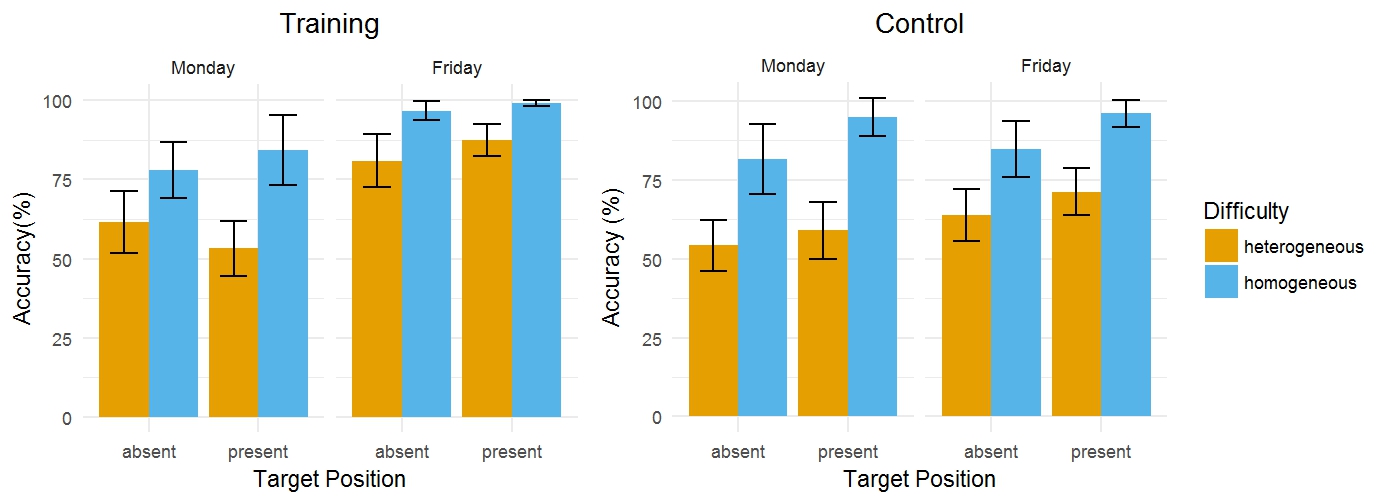


Figure 7. Mean position of the first ten fixations on the x-axis in the parallel condition (target absent trials) shown for the five consecutive days. Negative numbers extend to hemianopia side.

**Detection Task Results**



*Figure 3.* Accuracy data from the detection task shown separately on Monday and Friday for target absent and present trials and two search difficulties. Left panel shows accuracy in Training experiment and right panel Control experiment. The error bars show 95% confidence intervals.

The accuracy data from the detection task on two sessions are shown in figure 3. We only analysed data from 16 participants in this analysis as data from participant 16 Friday session was not recorded due to technical difficulties. As it is clear from the figure participants tend to perform better on the task in the second session, but this improvement is only modest in the control condition compared to the improvement we see following the training ( Figure 3). We calculated d’ as a measure of participant’s sensitivity to the target. To overcome the problem of extreme values in our data (values of 1) 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. We carried out a 2x2 repeated measure ANOVA (with difficulty and session as factors) and found a significant main effect of Search Difficulty [*F*(1,16)=112.88, *p*<.001, =.88] and session [*F*(1,16)=68.13, *p*<.001, =.81] but no significant interaction [*F*(1,16)=.15, *p*=.70, =.009]. Similarly in the control condition a 2x2 repeated measure ANOVA (with difficulty and session as factors) showed significant main effect of Search Difficulty [*F*(1,15)=96.54, *p*<.001, =.87] and session [*F*(1,15)=4.78, *p*=.045, =.24] but no significant interaction [*F*(1,16)=2.23, *p*=.16, =.13. Thus participants were more sensitive to the target in the second session both in the training group and control group, but size of the effect was larger following five day training.

**Object Naming Results**

Paired sample t-test showed that participants reported significantly more objects on Friday session [*M*=5.17, *SD*=.79], compared to the Monday session [*M*=4.69, *SD*=.61; *t*(16)=2.68,*p*=.016] in the training experiment**.** In contrast, participants did not reported significantly more objects in the control experiment on Friday session [*M*=4.16, *SD*=.74], compared to the Monday session [*M*=4.46, *SD*=1.09; *t*(16)=1.63,*p*=.12].

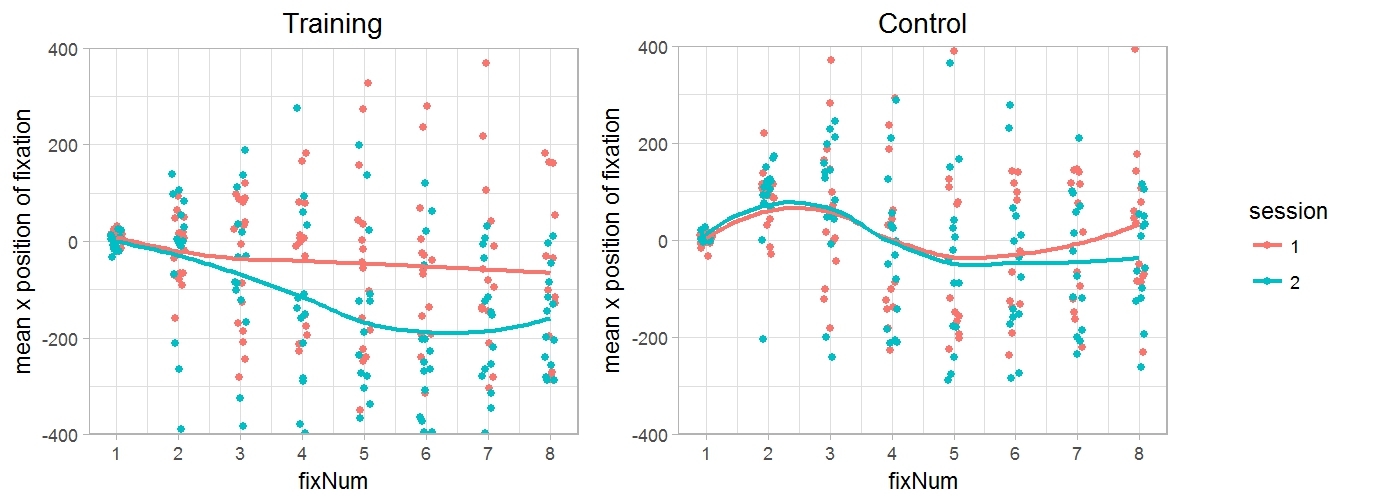
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Figure 4. Mean position of fixation on the x-axis shown for the first eight fixations, separately for Monday (red) and Friday (blue) sessions. Zero on the Y axis represents middle of the screen, and the negative numbers extend to the field where mask was applied.

We analysed mean position (on the x-axis) of the second, fourth and sixth fixation by session, for the two groups separately using 2x3 repeated measure ANOVA. In this analysis we selected only trials with minimum ten fixations (thus ten trials) in both sessions, and 14 participants met this criteria. In the training experiment this analysis showed main effect of Fixation Number [*F*(2,26)=5.21, *p*=.01, =.29], no significant effect of Session [*F*(1,13)=2.68, *p*=.13, =.17] and a significant interaction between the two factors [*F*(2,26)=6.16, *p*=.006, =.32]. In the control experiment neither main effect nor interaction was significant (all p<0.08).

**Discussion**

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.

**General Discussion**

We did observe faster reaction times and higher accuracy, but these were not associated with optimizing search strategy. Participants started searching the blind field more after the first session but they were far from optimal in the sense that they did not concentrate they search on the blind side.

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