# Efficient versus inefficient visual search as training for saccadic re-referencing to an extrafoveal location

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**Central vision loss is one of the leading causes of visual impairment in the elderly and its frequency is increasing. Without formal training, patients adopt an unaffected region of the retina as a new fixation location, a preferred retinal locus (PRL). However, learning to use the PRL as a reference location for saccades, that is, saccadic re-referencing, is protracted and time-consuming. Recent studies showed that training with visual search tasks can expedite this process. However, visual search can be driven by salient external features – leading to efficient search, or by internal goals, usually leading to inefficient, attention-demanding search. We compared saccadic re-referencing training in the presence of a simulated central scotoma with either an efficient or an inefficient visual search task. Participants had to respond by fixating the target with an experimenter-defined retinal location in the lower visual field. We observed that comparable relative training gains were obtained in both tasks for a number of behavioral parameters, with higher training gains for the trained task, compared to the untrained task. The transfer to the untrained task was only observed for some parameters. Our findings thus confirm and extend previous research showing comparable efficiency for exogenously and endogenously driven visual search tasks for saccadic re-referencing training. Our results also show that transfer of training gains to related tasks may be limited and needs to be tested for saccadic re-referencing-training paradigms to assess its suitability as a training tool for patients.**

## Introduction

In aging societies, the frequency of foveal vision loss increases. Age-related macular degeneration is one of the leading causes of visual impairment in the elderly (see Wong, et al., 2014). It negatively influences day-to-day living quality, bringing severe difficulties to everyday activities from leisure activities (Bullimore, 1990; Costela, Kajtezovic, & Woods, 2017; Elliott et al., 1997; Woods & Satgunam, 2011) to driving and navigation (Bowers, Peli, Elgin, McGwin, & Owsley, 2005). In age-related macular degeneration, which manifests as a damage to a part or parts of the retina, a patient often prefers to adopt an unaffected part of the retina as a new fixation point, often called a "preferred retinal locus" or PRL (Cummings, Whittaker, Watson, & Budd, 1985; Fletcher & Schuchard, 1997; Timberlake, et al., 1986; von Noorden & Mackensen, 1962). Records show that patients typically develop a PRL within the first 6 months (Cheung & Legge, 2005; Crossland, Culham, Kabanarou, & Rubin, 2005). Yet, the adoption of a PRL does not imply that patients can also use it as a reference point for saccades (Crossland et al., 2005; Fletcher & Schuchard, 1997; von Noorden & Mackensen, 1962; White & Bedell, 1990; Whittaker, Cummings, & Swieson, 1991), so that saccades lead to foveation of peripheral points of interest, which makes corrective saccades necessary (Fletcher, Schuchard, & Watson, 1999; Schuchard, 2005; Timberlake et al., 1986; von Noorden & Mackensen, 1962; Whittaker et al., 1991; White & Bedell, 1990; see also Heinen & Skavenski, 1992). As a consequence of this inefficient exploration of the environment patients' eye movement, patterns often change, resulting in less fixations, larger saccade amplitudes, and longer fixation durations (see also Geringswald, Herbik, Hoffmann, & Pollmann, 2013; Geringswald, Porracin, & Pollmann, 2016; Geringswald & Pollmann, 2015).

Recently, training paradigms using gaze-contingent scotoma simulation have been developed to achieve rapid saccadic re-referencing to a PRL in order to

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enable efficient exploration in the presence of central vision loss (Barraza-Bernal, Rifai, & Wahl, 2017; Ganesan, Melnik, Azanon, & Pollmann, 2023; Kwon, Nandy, & Tjan, 2013; Liu & Kwon, 2016; Pidcoe & Wetzel, 2006; Rose & Bex, 2017; Song, Ouchene, & Khan, 2021; Walsh & Liu, 2014; see also Maniglia, Visscher, & Seitz, 2020). Some of the previous saccadic re-referencing-training studies used visual search tasks as training paradigms. In one paradigm, participants searched for an O among C-shapes in the presence of a simulated central scotoma (Walsh and Liu, 2014). Searching for an O among C-shaped distractors is an inefficient search, leading to steep search time slopes (i.e. substantial search times per item in the search display). In contrast, in a gaze-contingent study from our laboratory, an X-shaped target needed to be fixated with a forced retinal location next to the simulated foveal scotoma (Ganesan et al., 2023). Compared to the O among C search, searching for an X among O-shapes is highly efficient, the target "pops out" from the distractors. Both training paradigms led to faster search times and more orderly gaze paths, showing that training was effective. In line with the visual search literature, we use the term "efficient" versus "inefficient" visual search to describe visual search tasks with low versus high search times per display item without making assumptions about the parallel or serial nature of the search (Wolfe, 1998).

However, the studies did not answer the question if using an efficient or an inefficient visual search paradigm for saccadic re-referencing after foveal vision loss was the better choice. Both kinds of training may have advantages. Saccadic re-referencing may be particularly difficult in an efficient search, because salient targets may trigger automatic saccade execution most strongly. Thus, saccadic re-referencing training with an efficient search paradigm may be best to counter the automatic response to salient targets. On the other hand, saccadic re-referencing training with an inefficient search may lead to better results when the search target is not immediately visible, affording an endogenously controlled search. Finally, saccadic re-referencing training – in order to be useful in everyday life – should lead to reliable saccadic re-referencing in both efficient and inefficient search, leading to the question how well one kind of search training will transfer to the other search type.

In order to investigate these questions, we made use of a well-known search asymmetry. Whereas the search of an O among C-shapes is inefficient, the reverse, search for a C among O-shapes, is efficient (Treisman & Souther, 1985). That is, in the latter, the target C will be discriminated in the periphery, typically followed by an automatic saccade to the target. In contrast, in the former, detection of the O-shaped target typically needs endogenously controlled eye movements, depending on the number of distractor items in the display. Therefore, by using both of these search types in a gaze-contingent search paradigm with normal-sighted participants, we were able to investigate both the training gains afforded by efficient and inefficient visual search paradigms as well as the training transfer between both kinds of search tasks.

Previous studies of saccadic re-referencing have analyzed oculomotor responses to single targets. For example, when describing the oculomotor patterns in patients with central vision loss, White and Bedell (1990), reported re-fixation eye movements, in which the observer would try to foveate the target with the now damaged fovea (as if their vision was intact), followed by a second eye movement that would bring the object of interest in the PRL area. Additionally, they described the motor reference shifts, when the saccades actually targeted the PRL without additional eye movements. In other studies, saccadic re-referencing was quantified as the position of the first saccade landing, and the percentage of trials in which the first saccade placed the target outside the scotoma (e.g. Kwon et al., 2013; Liu and Kwon, 2016; Maniglia, Visscher, et al., 2020). Although these studies allowed to analyze oculomotor processes in great detail, we chose to analyze saccadic re-referencing in a more naturalistic setting, in which target items appear together with numerous distractor items. Thus, we did not aim to distinguish between the re-fixation and the motor-reference shift components of saccadic re-referencing in our paradigm. Neither did we analyze the first or last saccade landing positions, but instead characterized visual search by its overall target acquisition latency and the efficiency of eye movements (number and duration of fixations and scan pattern ratio). We believe that improvements in exploration efficiency, characterized by these measures, are crucial for the success of saccadic re-referencing trainings for patients with central vision loss.

# Materials and methods

## Participants

Sixteen undergraduate students of the Otto-von-Guericke University Magdeburg took part in the experiment. Half of the participants (8 participants = 2 men and 5 women, and 1 other); age range = 21–34, age M = 25.75, SD = 1.65) were randomly assigned to the C among O training condition and the other half of the participants (8 participants = 3 men and 5 women), age range = 20–28, age M = 23.63, SD = 0.99) to the O among C training condition. Previous research (Treisman & Souther, 1985) obtained significant search asymmetries for C among O versus O among C search with eight participants per group, thus, our sample

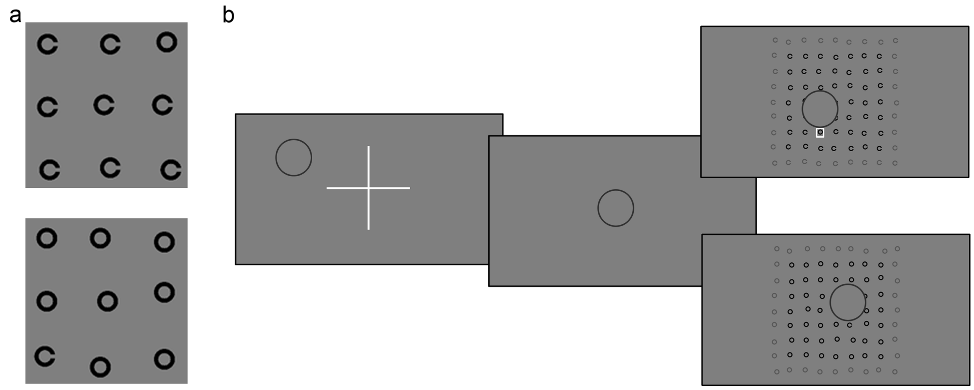


Figure 1. Illustration of the training groups and tasks. (**a**) Two training conditions – the O among C is depicted on the top and C among O is depicted on the bottom display. (**b**) Time course of the trial. The trial stated by a fixation, followed by a blank screen (500 ms). The trial started only if the participant fixated the fixation cross for 1 seconds. In this example, to improve visibility, we outline the position of the scotoma with a dark edge, but in the experiment the scotoma matched in color the background and no dark edge was shown. The participants had to search for the target among distractors in the presence of scotoma and "fixate" the target with the FRL location. The location was highlighted in white during the practice and training (top search display). The white reference was not present during the pre- and post-test (bottom search display). See text for details (stimuli not shown to scale).

size was also set to eight participants per group. All participants reported normal or corrected to normal vision. The experiment was carried out with regard to the ethical standards of the Declaration of Helsinki. The experiment was approved by the local Ethical Committee of the Otto-von-Guericke University Magdeburg. All participants provided informed consent prior to their participation. Participants either received a monetary compensation (8 Euros/hour) or received course credits.

## Apparatus

Python 3.6, the Psychopy toolbox (Peirce, 2007) and the pylink toolbox (SR Research Ltd., Mississauga, Ontario, Canada) running on an Ubuntu Linux computer were used to control the stimulus presentation and to collect data. Stimuli were presented on a 24-inch Iiyama Prolite GB2488HSU monitor. The 53.1 cm wide and 29.9 cm high monitor was set at a resolution of 1920 × 1080 pixels and a refresh rate of 144 Hz. The stimuli were viewed binocularly from 60 cm. The viewing position was stabilized with a chin- and headrest. Eye movements were recorded using an Eye Link 1000 eye-tracker positioned in a desktop mount (SR Research Ltd., Mississauga, Ontario, Canada) at a 1000 Hz sampling rate. The experiment took place in a dimly lit room. During the experiment, the participant's dominant eye was tracked. The delay between the eye position update and the stimulus update, measured using a setup that included a photodiode and an artificial eye driven by a stepper motor (Felßberg & Strazdas, 2022), was 16.6 ms.

## Stimuli

Stimulus displays consisted either of one "C"-target and 80 "O"-distractors (efficient search; C among O task) or one "O"-target and 80 "C"-distractors (inefficient search; O among C task) arranged on a square 9 × 9 configuration (see Figure 1). The target did not appear on the edge and the center (center 5 position) on the grid. The target and distractors were shown in the Sloan font, with height of 1 degree and the stroke width of 0.2 degrees. The search display spanned an area of 23 degrees × 23 degrees. The position of each element on the grid was jittered with an offset selected randomly from −0.2 degrees, −0.1 degrees, 0 degrees, 0.1 degrees, or 0.2 degrees horizontally and vertically (on x and y-axis) to prevent collinearity. Search items were presented in black (0.33 cd/m$^2$) on a gray (68.82 cd/m$^2$) background. Stimuli on the edge of the display were presented in dark gray (26.4 cd/m$^2$).

## Tasks

Participants were instructed to find the target as fast as possible, and, once they have found it, to peripherally view the target with the forced retinal location (FRL), spanning a 1.5 degrees × 1.5 degrees area, located 5 degrees below the fixation. A gaze contingent sharp-edged, fully opaque (invisible on the background, for example, matching the color of the background) of 4 degrees in radius covered the central vision throughout the search task. First, the participants were asked to fixate a fixation cross for

1 second. After that, a blank screen appeared for 500 ms, and the search display was shown. The trial ended after participants peripherally viewed the target with the FRL for 500 ms. If the participants could not make a successful 500 ms fixation on the target with their FRL, the trial finished after 60 seconds. A blank screen was shown for 500 ms before the start of a new trial. One block consisted of 44 trials. Participants were encouraged to take a short break after every block. A standard nine-point calibration and validation procedure was performed at the beginning of every block. Before commencing each session (or task in the pre- and post-test), participants completed 20 practice trials. The FRL area was highlighted with a white (238.41 cm/m$^2$) frame during both the practice and the training sessions.

## Design

The experiment consisted of a pre-test session, three training sessions, and a post-test session. In the pre-test and post-test sessions, all participants completed two types of search tasks – three blocks of the efficient search task (C among O), and three blocks of the inefficient search task (O among C). The order of tasks (efficient search first or second) was counterbalanced across participants. The participants were divided into groups for the training sessions. Half of the participants completed training with the efficient search task, and the other half completed the training with the efficient search task (8 blocks per training session). Participants completed 1056 training trials in total.

## Data preprocessing, extraction, and analysis

Gaze data was processed at 1000 Hz. Gaze position data were smoothed by using a running average on velocity samples to suppress high-frequency noise. We used the standard Eyelink algorithm to extract saccades and fixations. Trials on which the participant was not able to find the target were excluded from the analysis.

We quantified target acquisition latency, that is, the time from display onset until the onset of the last fixation, excluding the 500 ms fixation period during which the target was fixated with the FRL. This parameter captured the overall performance improvement. We quantified the number of fixations that the participants needed to find the target and the average fixation duration. The last fixation and its duration were again excluded from the calculations. To quantify the efficiency of eye movements, we quantified the scan pattern ratio. The scan pattern ratio was calculated as the ratio between the total spatial displacement of all saccades and the shortest distance between the fixation at the start of the trial and the final FRL position (Henderson, Weeks, & Hollingworth, 1999). The lower scan pattern ratio indicated a direct and efficient search. Overall, number of fixations, average fixation duration, and scan pattern ratio yielded additional insights into the processes behind a reduced target acquisition latency. We also computed target foveation, that is, the absolute number of fixations within the 1-degree radius around the target, that is, the area where the target is covered by the scotoma. Target foveation is the parameter most closely related to saccadic re-referencing in our study. Note that we expected that the participants' gaze would cover the target from time to time during the search, because the participants had to search a cluttered display. However, we hypothesized that the frequency of target (area) fixations should decrease as the participants learned to adapt to the scotoma and re-referenced their saccades successfully.

We analyzed how the participants' performance changed with training using mixed model ANOVAs on the five parameters above. For all analyses, the Greenhouse–Geisser correction was reported if Mauchly's test indicated that the assumption of sphericity had been violated. The a-criterion was set to $a = 0.01$ to account for the family of five parameters tested. We followed the ANOVAs by planned comparisons of the transfer between the tasks.

We excluded all trials with target acquisition latency greater or less than 3 × standard deviation as well as trials with a scan-pattern ratio > 100. This resulted in the exclusion of 3.12% of the data. We also computed the normalized outcomes for each variable, by computing (AvgVarPre-AvgVarPost)/(AvgVarPre + AvgVarPost) for each subject, where AvgVarPre is the average across trials for each participant in the pre-test, and AvgVarPost is the average in the post-test separately for target acquisition latency, number of fixations, fixation duration, scan pattern ratio, and target foveation. This was done to account for pre-test search time differences due to search asymmetries between the tasks. We analyzed the training gains using mixed model ANOVAs, followed by the analysis of the transfer between the tasks. In addition, we assessed whether the training gains were positive for both trained and untrained tasks with one sample *t*-tests.

# Results

The results are summarized in Figure 2 and Table 1. We compared target acquisition latency, number of fixations, fixation durations, scan pattern ratio, and number of fixations around the target (see Methods for details) using separate mixed-design ANOVAs with

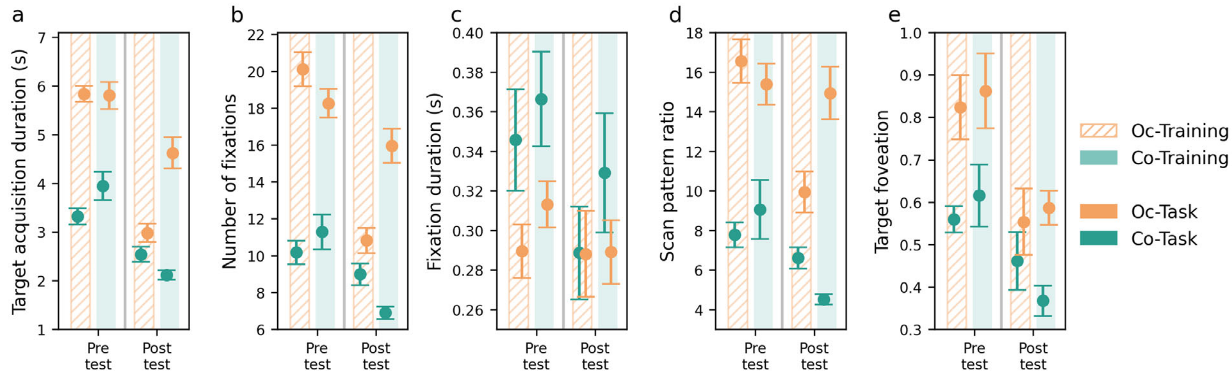


Figure 2. Average target acquisition latencies (**a**), number of fixations (**b**), fixation duration (**c**), scan pattern ratios (**d**), and target foveation (**e**) for pre- and post-training. Plots show data separated for training (C among O [light green background] and O among C training [shaded orange background]) and task (C among O [green] and O among C task [orange]). Error bars indicate standard errors of the mean. A small horizontal jitter was added to the data points to reduce overlap of the error bars. Oc-training = O among C training; Co-training = C among O training; Oc-task = O among C task; Co-task = C among O task.

| Effects and interactions | Target acquisition latency | Number of fixations | Fixation duration | Scan pattern ratio | Target foveation |
|---|---|---|---|---|---|
| Main effect of Task (C among O task versus O among C task) | $\mathbf{F(1, 14) = 365.38}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.96}$ | $\mathbf{F(1, 14) = 497.68}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.97}$ | $\mathbf{F(1, 14) = 13.72}$, $\mathbf{p = 0.002}$, $\mathbf{\eta_p^2 = 0.50}$ | $\mathbf{F(1, 14) = 135.77}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.91}$ | $\mathbf{F(1, 14) = 37.90}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.73}$ |
| Main effect of session (pre- or post-task) | $\mathbf{F(1, 14) = 193.62}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.93}$ | $\mathbf{F(1, 14) = 99.53}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.88}$ | $F(1, 14) = 6.93$, $p = 0.02$, $\eta_p^2 = 0.33$ | $\mathbf{F(1, 14) = 38.34}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.73}$ | $\mathbf{F(1, 14) = 22.70}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.62}$ |
| Main effect of training group (trained with C among O training versus trained with O among C training) | $F(1, 14) = 3.25$, $p = 0.09$, $\eta_p^2 = 0.19$ | $F(1, 14) = 0.42$, $p = 0.53$, $\eta_p^2 = 0.03$ | $F(1, 14) = 0.59$, $p = 0.46$, $\eta_p^2 = 0.04$ | $F(1, 14) = 0.42$, $p = 0.53$, $\eta_p^2 = 0.03$ | $F(1, 14) = 0.01$, $p = 0.91$, $\eta_p^2 < 0.01$ |
| Interaction between task and training groups | $\mathbf{F(1, 14) = 13.50}$, $\mathbf{p < 0.01}$, $\mathbf{\eta_p^2 = 0.49}$ | $\mathbf{F(1, 14) = 11.65}$, $\mathbf{p = 0.004}$, $\mathbf{\eta_p^2 = 0.45}$ | $F(1, 14) = 0.81$, $p = 0.38$, $\eta_p^2 = 0.06$ | $F(1, 14) = 3.54$, $p = 0.08$, $\eta_p^2 = 0.20$ | $F(1, 14) = 0.68$, $p = 0.43$, $\eta_p^2 = 0.05$ |
| Interaction between session and task | $F(1, 14) = 5.52$, $p = 0.034$, $\eta_p^2 = 0.28$ | $\mathbf{F(1, 14) = 10.198}$, $\mathbf{p = 0.007}$, $\mathbf{\eta_p^2 = 0.42}$ | $F(1, 14) = 5.04$, $p = 0.04$, $\eta_p^2 = 0.27$ | $F(1, 14) = 0.35$, $p = 0.56$, $\eta_p^2 = 0.03$ | $F(1, 14) = 2.95$, $p = 0.11$, $\eta_p^2 = 0.17$ |
| Interaction between session and training groups | $F(1, 14) = 1.71$, $p = 0.21$, $\eta_p^2 = 0.11$ | $F(1, 14) = 4.82$, $p = 0.046$, $\eta_p^2 = 0.26$ | $F(1, 14) = 0.004$, $p = 0.95$, $\eta_p^2 < 0.01$ | $F(1, 14) = 1.84$, $p = 0.20$, $\eta_p^2 = 0.12$ | $F(1, 14) = 0.70$, $p = 0.42$, $\eta_p^2 = 0.05$ |
| An interaction among session, task, and training groups | $\mathbf{F(1, 14) = 20.18}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.59}$ | $\mathbf{F(1, 14) = 29.15}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.68}$ | $F(1, 14) = 1.92$, $p = 0.19$, $\eta_p^2 = 0.12$ | $\mathbf{F(1, 14) = 17.87}$, $\mathbf{p < 0.001}$, $\mathbf{\eta_p^2 = 0.56}$ | $F(1, 14) = 1.54$, $p = 0.24$, $\eta_p^2 = 0.10$ |

Table 1. Results of mixed model ANOVAs with training group (trained with C among O training or trained with O among C training) as a between-subjects factor, and task (C among O task and O among C task) and session (pre-test and post-test) as within-subjects factors for target acquisition latency, number of fixations, fixation durations, scan pattern radio, and target foveation. Significant results are printed in bold. Due to Bonferroni correction the alpha value is 0.01.

task (O among C and v.v.) and session (pretest and post-test) as the within-subject factors and training group (O among C and v.v.) as the between-subjects factor.

As expected, the analysis showed a main effect of task, after Bonferroni correction for five tests (see Table 1 for the ANOVA results). The data replicated the well-known search asymmetry between

| Effects and interactions | Target acquisition latency | Number of fixations | Fixation duration | Scan pattern ratio | Target foveation |
|---|---|---|---|---|---|
| *Trained task* | | | | | |
| Main effect of session (pre- or post-task) | **$F(1, 14) = 197.47$, $p < 0.001$, $\eta_p^2 = 0.93$** | **$F(1, 14) = 127.19$, $p < 0.001$, $\eta_p^2 = 0.90$** | $F(1, 14) = 1.26$, $p = 0.28$, $\eta_p^2 = 0.083$ | **$F(1, 14) = 45.29$, $p < 0.001$, $\eta_p^2 = 0.76$** | **$F(1, 14) = 19.85$, $p < 0.001$, $\eta_p^2 = 0.58$** |
| Main effect of training group (trained with C among O training versus trained with O among C training) | **$F(1, 14) = 30.94$, $p < 0.001$, $\eta_p^2 = 0.69$** | **$F(1, 14) = 42.43$, $p < 0.001$, $\eta_p^2 = 0.75$** | $F(1, 14) = 3.75$, $p = 0.07$, $\eta_p^2 = 0.21$ | **$F(1, 14) = 21.67$, $p < 0.001$, $\eta_p^2 = 0.61$** | $F(1, 14) = 5.46$, $p = 0.035$, $\eta_p^2 = 0.28$ |
| Interaction between session and training groups | **$F(1, 14) = 9.46$, $p < 0.01$, $\eta_p^2 = 0.40$** | **$F(1, 14) = 16.34$, $p = 0.001$, $\eta_p^2 = 0.54$** | $F(1, 14) = 1.10$, $p = 0.31$, $\eta_p^2 = 0.07$ | $F(1, 14) = 1.56$, $p = 0.23$, $\eta_p^2 = 0.10$ | $F(1, 14) = 0.03$, $p = 0.86$, $\eta_p^2 < 0.01$ |
| *Untrained task* | | | | | |
| Main effect of session (pre- or post-task) | **$F(1, 14) = 20.42$, $p < 0.001$, $\eta_p^2 = 0.59$** | $F(1, 14) = 6.80$, $p = 0.021$, $\eta_p^2 = 0.33$ | **$F(1, 14) = 20.17$, $p < 0.001$, $\eta_p^2 = 0.59$** | $F(1, 14) = 1.35$, $p = 0.27$, $\eta_p^2 = 0.09$ | **$F(1, 14) = 13.02$, $p = 0.003$, $\eta_p^2 = 0.48$** |
| Main effect of training group (trained with C among O training versus trained with O among C training) | **$F(1, 14) = 62.35$, $p < 0.001$, $\eta_p^2 = 0.81$** | **$F(1, 14) = 69.71$, $p < 0.001$, $\eta_p^2 = 0.83$** | $F(1, 14) = 0.31$, $p = 0.58$, $\eta_p^2 = 0.02$ | **$F(1, 14) = 41.58$, $p < 0.001$, $\eta_p^2 = 0.75$** | $F(1, 14) = 7.70$, $p = 0.015$, $\eta_p^2 = 0.36$ |
| Interaction between session and training groups | $F(1, 14) = 0.86$, $p = 0.37$, $\eta_p^2 = 0.06$ | $F(1, 14) = 0.71$, $p = 0.42$, $\eta_p^2 = 0.048$ | $F(1, 14) = 3.32$, $p = 0.09$, $\eta_p^2 = 0.19$ | $F(1, 14) = 0.27$, $p = 0.61$, $\eta_p^2 = 0.02$ | $F(1, 14) = 2.95$, $p = 0.108$, $\eta_p^2 = 0.174$ |

Table 2. Results of ANOVAs with training group (trained with C among O training or trained with O among C training) as a between-subjects factor, and session (pre-test and post-test) as within-subjects factors computed separately for the two tasks (trained [e.g. C among O task for the C among O training] and untrained) for target acquisition latency, number of fixations, fixation durations, scan pattern radio, and target foveation. Significant results are printed in bold. Due to Bonferroni correction the alpha value is 0.01. See text for additional information.

the tasks (Treisman & Souther, 1985) for search with scotoma simulation (see Figure 2). As predicted, performance was less efficient in the O among C task compared to the C among O task in all five parameters, that is, target acquisition latency, number of fixations, fixation duration, scan pattern ratio, and target foveation.

Concerning the effectiveness of training, the analyses showed a significant main effect of Session, due to improvements from pretest to post-test, for all variables except fixation duration (see Table 1). Participants had faster target acquisition latencies, made less fixations, and shorter scan pattern ratios after training. In addition, the target foveation, although common in the pre-test, decreased with training, as would be expected following saccadic re-referencing.

The interaction of task × session was only significant for the number of fixations, with stronger reductions for the O among C task in the post-test. The main effect of the training group was not significant for any of the variables. Likewise, no significant interactions between training group and session were observed. However, not surprisingly, training was most beneficial for the trained task, leading to significant task × training group interactions for all variables but fixation duration and target foveation. Moreover, significant three-way interactions were observed for all variables except fixation duration and target foveation. To further analyze these interactions, and specifically the theoretically important effects of training on the trained and not trained tasks, we calculated two separate ANOVAs with the session (pre and post) and training groups (C among O and O among C) on the data from the trained and the untrained task (Table 2).

Performance in the trained task improved from pre-test to post-test in all parameters except fixation duration. In the untrained task, improvement between the pre- and post-test was only seen after Bonferroni correction in target acquisition latency, fixation duration (with a decrease in fixation durations with training), and target foveation. The main effect of the training group yielded significant effects for target

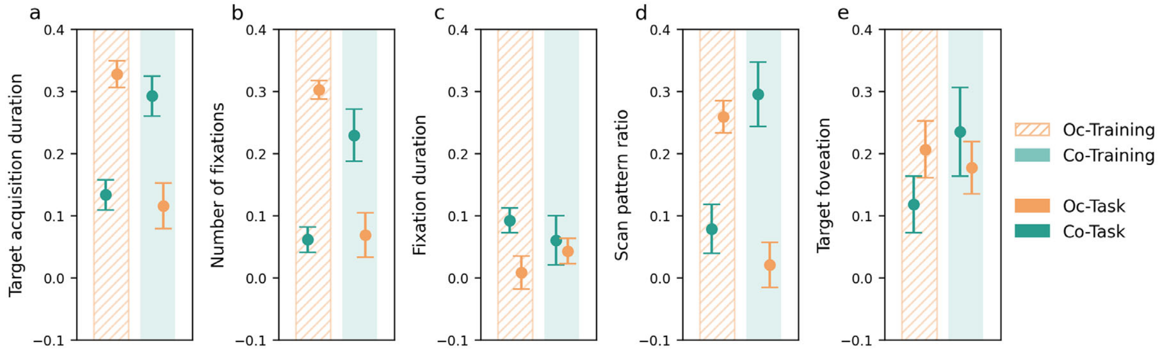


Figure 3. Normalized training outcomes. Average normalized outcomes in target acquisition latencies (**a**), number of fixations (**b**), fixation duration (**c**), scan pattern ratio (**d**), and target foveation (**e**) for pre- and post-training. Plots show data separated for training (C among O [light green background] and O among C training [shaded orange background]) and task (C among O [green] and O among C task [orange]). Error bars indicate standard errors of the mean. A small horizontal jitter was added to the data points to reduce overlap of the error bars. Oc-training = O among C training; Co-training = C among O training; Oc-task = O among C task; Co-task = C among O task.

| Effects and interactions | Target acquisition latency | Number of fixations | Fixation duration | Scan pattern ratio | Target foveation |
|---|---|---|---|---|---|
| Main effect of task (C among O task, O among C task) | $F(1, 14) = 0.07$, $p = 0.80$, $\eta_p^2 = 0.005$ | $F(1, 14) = 1.59$, $p = 0.227$, $\eta_p^2 = 0.102$ | $F(1, 14) = 5.81$, $p = 0.03$, $\eta_p^2 = 0.29$ | $F(1, 14) = 1.31$, $p = 0.272$, $\eta_p^2 = 0.09$ | $F(1, 14) = 0.13$, $p = 0.72$, $\eta_p^2 = 0.009$ |
| Main effect of training group (trained with C among O training versus trained with O among C training) | $F(1, 14) = 0.89$, $p = 0.36$, $\eta_p^2 = 0.06$ | $F(1, 14) = 1.02$, $p = 0.33$, $\eta_p^2 = 0.07$ | $F(1, 14) = 0.01$, $p = 0.93$, $\eta_p^2 < 0.01$ | $F(1, 14) = 0.06$, $p = 0.81$, $\eta_p^2 < 0.01$ | $F(1, 14) = 0.43$, $p = 0.53$, $\eta_p^2 = 0.03$ |
| Interaction between task and training group | **$F(1, 14) = 29.778$, $p < 0.001$, $\eta_p^2 = 0.68$** | **$F(1, 14) = 39.535$, $p < 0.001$, $\eta_p^2 = 0.74$** | $F(1, 14) = 2.50$, $p = 0.14$, $\eta_p^2 = 0.15$ | **$F(1, 14) = 30.08$, $p < 0.001$, $\eta_p^2 = 0.68$** | $F(1, 14) = 3.02$, $p = 0.104$, $\eta_p^2 = 0.18$ |

Table 3. Results of mixed model ANOVAs with training group (trained with C among O training or trained with O among C training) as a between-subjects factor, and task (C among O task and O among C task) as within-subjects factors for normalized target acquisition latency, number of fixations, fixation durations, scan pattern radio, and target foveation. Significant results are printed in bold.

acquisition latency, number of fixations, and scan pattern ratio, reflecting the different efficiency of the two search tasks. Importantly, a significant interaction between session and training group, that is, an improvement from pre- to post-test dependent on the trained task, was only observed for target acquisition latency and the number of fixations of the trained task, with particularly large improvements in the O among C training group.

We further asked if the observed training gains depended on the difference in search efficiency between the two search tasks. Therefore, we computed normalized training gains (positive gains indicating a successful improvement in training and negative or zero gains suggesting unsuccessful training, see Methods for details). ANOVAs on the normalized data revealed comparable patterns for target acquisition latency, number of fixations, and scan pattern ratio, namely a significant interaction between the task and the training groups in the absence of significant main effects of task and training groups (Figure 3, Table 3). This pattern reflected that training gains were overall comparable, but clearly higher for the trained task than the untrained task (Figure 3, Table 4). This indicated that training was most successful for the trained task, but was there still a training effect for the untrained task? To answer this question, we calculated sets of $t$-tests for the five behavioral parameters for each task to evaluate if training scores were positive. For participants who were trained with the O among C training, the gains for the untrained (C among O) task were significantly positive (after Bonferroni correction) only for target acquisition latency and fixation duration (Table 5). For the reverse (C among O training), we did

| | Differences between trained and untrained task in C among O training group | Differences between trained and untrained task in O among C training | Difference between the training groups in trained tasks | Difference between the training groups in untrained tasks |
|---|---|---|---|---|
| Target acquisition latency | **$t = 3.68$, $p_{holm} = 0.007$** | **$t = 4.04$, $p_{holm} = 0.006$** | $t = 0.80$, $p_{holm} = 0.86$ | $t = 0.40$, $p_{holm} = 0.86$ |
| Number of fixations | **$t = 3.55$, $p_{holm} = 0.01$** | **$t = 5.34$, $p_{holm} < 0.001$** | $t = 1.60$, $p_{holm} = 0.24$ | $t = 0.16$, $p_{holm} = 0.87$ |
| Scan pattern ratio | **$t = 4.69$, $p_{holm} = 0.002$** | **$t = 3.07$, $p_{holm} = 0.025$** | $t = 0.62$, $p_{holm} = 0.67$ | $t = 0.98$, $p_{holm} = 0.67$ |

Table 4. Results of planned comparisons for the significant interaction between task and training groups. Multiple comparisons were adjusted with the Holm method (alpha value = 0.05). Significant results are printed in bold.

| Parameter | Training | Task | Statistic |
|---|---|---|---|
| Target acquisition latency | C among O | Trained | **$t(7) = 8.53$, $p < 0.001$** |
| | | Untrained | $t(7) = 2.96$, $p = 0.011$ |
| | O among C | Trained | **$t(7) = 14.39$, $p < 0.001$** |
| | | Untrained | **$t(7) = 5.13$, $p < 0.001$** |
| Number of fixations | C among O | Trained | **$t(7) = 5.12$, $p < 0.001$** |
| | | Untrained | $t(7) = 1.81$, $p = 0.06$ |
| | O among C | Trained | **$t(7) = 19.08$, $p < 0.001$** |
| | | Untrained | $t(7) = 2.83$, $p = 0.013$ |
| Scan pattern ratio | C among O | Trained | **$t(7) = 5.33$, $p < 0.001$** |
| | | Untrained | $t(7) = 0.53$, $p = 0.31$ |
| | O among C | Trained | **$t(7) = 9.29$, $p < 0.001$** |
| | | Untrained | $t(7) = 1.88$, $p = 0.05$ |
| Fixation duration | C among O | Trained | $t(7) = 1.43$, $p = 0.098$ |
| | | Untrained | $t(7) = 1.95$, $p = 0.046$ |
| | O among C | Trained | $t(7) = 0.30$, $p = 0.38$ |
| | | Untrained | **$t(7) = 4.35$, $p = 0.002$** |
| Target foveation | C among O | Trained | $t(7) = 3.08$, $p = 0.009$ |
| | | Untrained | $t(7) = 3.92$, $p = 0.003$ |
| | O among C | Trained | **$t(7) = 4.23$, $p = 0.002$** |
| | | Untrained | $t(7) = 2.43$, $p = 0.023$ |

Table 5. Analysis of training gains. To evaluate the results of the training, we conducted separate (directional) one sample *t*-tests on the normalized training data. The alternative hypothesis specifies that the mean is greater than 0. Bonferroni corrected alpha for 20 comparisons = 0.0025. Significant results are printed in bold.

not observe significant reductions with the untrained (O among C) task. Thus, transfer of training was only observed for selected parameters in one direction, from training with an inefficient search to an efficient search.

## Discussion

A central problem of foveal vision loss is the need to re-reference saccades to an extrafoveal PRL. Although saccades typically lead to the foveation of peripheral items, enabling high resolution vision, in the case of a foveal scotoma this foveation is maladaptive, requiring corrective saccades to look at the item with the PRL. Here, we explored the use of two visual search tasks to train saccadic re-referencing to a PRL. Using eye tracking in normal-sighted participants, we simulated a central scotoma and required participants to look at a visual search target with a predetermined extrafoveal location. In line with previous results (Ganesan et al., 2023), we found that training with this task improved search performance, demonstrated by reduced target acquisition times and a number of eye movement parameters. Crucially, we trained participants with an efficient search task – search for a C-shape among O-shaped distractors – and with an inefficient search task – search for an O among C-shapes – in the presence of a simulated central scotoma. The rationale for varying search efficiency was to investigate saccadic re-referencing when saccades are driven mainly by salient external stimuli – in efficient search – and when they are mainly controlled endogenously – in inefficient search.

Visual search has previously been used successfully as a training paradigm for saccadic re-referencing (Ganesan et al., 2023; Kwon et al., 2013; Walsh & Liu, 2014). However, to our knowledge, only the studies by Walsh and Liu (2014) and Ganesan et al. (2023) had visual search paradigms that were known to lead to an inefficient, endogenously driven search (Walsh & Liu, 2014), and an efficient, exogenously driven search (Ganesan et al., 2023). Whereas these studies demonstrated that both an efficient and an inefficient visual search can successfully be used as a training paradigm for saccadic re-referencing, no study so far has simultaneously compared both kinds of tasks as training paradigms for saccadic re-referencing training. Both studies also did not investigate transfer between saccadic re-referencing training with exogenously and endogenously driven visual search. In the present study, we aimed to investigate these questions.

Visual search for salient targets (i.e. an efficient search) might be the easier training task, particularly for the often elderly patients with central vision loss, for example, caused by age-related macular degeneration. On the other hand, salient targets may attract foveating saccades more potently than non-salient targets, making re-referencing saccades to a PRL more demanding. However, we did not observe such an asymmetry between search tasks. After correcting for inherent search time differences between the tasks, that is, faster search times in efficient visual search, comparable training gains were obtained in both tasks (see Figure 3). Participants showed improvements in target acquisition latencies from pre-test to post-test, and, similarly, reduced fixation numbers and scan pattern ratios. The increase in search efficiency that these measures indicated were at least in part due to a reduction of foveating saccades over the course of training. Thus, as intended, the reduction of foveating saccades that are beneficial in normal vision but maladaptive in the presence of foveal vision loss was achieved with both visual search tasks.

Oculomotor guidance is always an interplay between peripheral vision and subsequent eye movements to bring a peripheral stimulus into fixation. It is well known that covert attention precedes the actual saccade in moving to a peripheral saccade target location (Kowler, Anderson, Dosher, & Blaser, 1995; Deubel & Schneider, 1996). It is noteworthy that, to master our task, participants actually had to fixate on the target with the FRL, in distinction to previous studies that used gaze-contingent stimulus presentation but required a manual response, thereby enabling successful target responses when the FRL was just near enough to the target to discriminate it from the distractors. Our results – reduced target acquisition latency, reduced fixations, and improved scan pattern ratio – indicate that as the session went by, participants fixated the target more directly, including avoiding foveation, that is, covering the target with the scotoma, suggesting that saccadic re-referencing was successful. Nevertheless, it needs to be pointed out that our methods are more indirect measures than measurements of fixation locations in studies with single target displays (e.g. Kwon et al., 2013; Liu & Kwon, 2016). These measurements were not really appropriate here. For instance, in a display with many items, the first fixation may be a target foveation attempt or an exploratory saccade and their ratio may differ for efficient and inefficient search tasks. Likewise, different from studies using a manual response format, the last fixation in our experiment had to place the target in the FRL, because this was the required response. Thus, a heatmap of the first or last fixation would not have been informative regarding the success of saccadic re-referencing.

As both exogenously and endogenously driven search occurs in everyday life, one would like to have a training paradigm that achieves saccadic re-referencing in both kinds of search. This brings up the question of transfer of training. Clearly, training gains were strongest in the trained task, respectively, with only partial transfer of training gains to the untrained task.

Nevertheless, it is noteworthy that we observed some transfer of learning benefits between the two visual search tasks. Although the benefits were greater for the trained task, nevertheless, target acquisition latency and fixation duration were reduced in an untrained efficient search, after training with an inefficient search. Transfer of training is notoriously difficult to achieve (Ball & Sekuler, 1987; Crist, Kapadia, Westheimer, & Gilbert, 1997; Fiorentini & Berardi, 1981; Schoups, Vogels, & Orban, 1995; but see Ahissar & Hochstein, 1997; Liu & Weinshall, 2000), so the present results should not be underestimated. However, the limited amount of transfer between two closely parallelized tasks that used the identical stimuli but differed in search efficiency should serve as a caveat that transfer of training cannot be taken for granted, even for "near transfer" between rather similar visual tasks. Specifically, as efficient visual search is thought to be driven mainly exogenously by salient stimuli, whereas an inefficient search depends on endogenous control, a certain independence of exogenous versus endogenous search processes (Chica, Bartolomeo, & Lupiáñez, 2013; Jonides, 1981; Müller & Rabbitt, 1989) may explain why transfer between an efficient and an inefficient search task was incomplete. In particular, the unidirectional transfer from inefficient to efficient search may be due to trained automatic saccadic re-referencing, which can be used directly to move a peripheral pop-out target to the FRL. The same automated saccadic re-referencing mechanism may be less applicable initially when an efficient, pop-out, search (during training) changes to an inefficient search, requiring endogenously controlled eye movements. In addition, training with the inefficient search task may lead to an increased number of FRL fixations per trial because of the higher number of fixations until the target is fixated.

Further worthwhile research questions would be if training on both tasks yields better results. A potential alternative may also be the use of a visual singleton search for the training. In a singleton search, the target is not defined by a predefined feature (like the C or O shapes), but it is the only item in the search display that differs from all other items. This also means that the target item can differ from trial to trial. In a singleton search, thus, participants cannot search for a given feature, but are thought to be in a singleton detection mode, looking out for salient differences between items (Bacon & Egeth, 1994), although it has been shown that further factors like previous target features may affect singleton search (see e.g. Lamy & Egeth, 2003). It may be that a singleton search is a particularly adequate paradigm for saccadic re-referencing training, because it demands both exogenous and endogenous search processes. In any case, transfer of training gains to relevant visual activities like reading or object recognition should be tested (e.g. Barraza-Bernal, 2017; Liu & Kwon, 2016).

As in our study, central vision loss has been repeatedly simulated with gaze contingent displays (e.g. Aguilar & Castet, 2011; Chen, et al., 2019; Ganesan et al., 2023; Kwon, Nandy, & Tjan, 2013; Liu & Kwon, 2016; Maniglia, Jogin, Visscher, & Seitz, 2020; Prahalad & Coates, 2020; Rose & Bex, 2017; Varsori, Perez-Fornos, Safran, & Whatham, 2004; Walsh & Liu, 2014). However, it has been recently questioned whether the gaze-contingent simulation of vision loss can even approximate natural vision loss (Ağaoğlu, Fung, & Chung, 2022). Agaoglu and colleagues (Agaoglu, Fung, & Chung, 2022) trained participants to use a PRL as a saccade target. After training, participants completed trials with and without artificial scotoma. The results showed that when no scotoma was shown, participants could make accurate saccades instantly. Thus, the authors suggested that participants developed a strategy rather than a genuine adaptation. However, an alternative explanation might be that the normal-sighted participants developed a context-dependent adaptation, that is, saccadic re-referencing only in the presence of a simulated scotoma. For related context-dependent effects see, for example, Cosman and Vecera (2013). Although the question which mechanisms may lead to improved performance is of genuine scientific interest, it should be noted that for practical purposes of patient training, improved search speed, driven by more efficient exploration of the environment with eye movements, is crucial.

Although previous studies show a great potential of search tasks for training oculomotor control in the presence of simulated central vision loss, certain aspects need to be adjusted for the training of patients with central vision loss. Duration of the training protocol, as well as simplicity of the task will be crucial for patient training. Because Ganesan et al. (2023) observed the most pronounced improvements early in training with a related gaze-contingent training paradigm, we here used a three-session training protocol. Our results show improvements in both trained and untrained (although not for all parameters) tasks indicating that a short training duration is effective in achieving training benefits. However, Ganesan et al. (2023) also showed additional training benefits after extended training (up to 25 hours), in agreement with previous studies (e.g. Kwon et al., 2013; Walsh & Liu, 2014). Further worthwhile research questions would be if prolonged training leads to more transfer and, particularly, if training on both tasks yields better results.

Patients, due to their typically late age, might require more but shorter training sessions. Simplicity of the task is another important consideration for proposing the training to the patient group. Visual search difficulty can easily be adjusted: size and number of items in the display can be adjusted to the patient's acuity and performance at the start (Liu, Kuyk, & Fuhr, 2007). Finally, some technical aspects of the training need to be addressed. Our participants, as well as participants in many previous studies (e.g. Ganesan et al., 2023, Kwon et al., 2013; Walsh & Liu, 2014), were young adults with normal or corrected-to-normal vision, thus we used an FRL located in the lower visual field. Patients with age-related macular degeneration, however, typically have an already developed region that they prefer using (e.g. a PRL; Cummings et al., 1985; Fletcher & Schuchard, 1997; Timberlake et al., 1986; von Noorden & Mackensen, 1962). In patients with central vision loss, the position of the FRL should be adjusted so that it borders the area of vision loss. In addition, providing a scotoma-overlay that indicates the dimensions of the patient's with age-related macular degeneration own natural scotoma could be beneficial (see also Janssen & Verghese, 2016; Pratt. Stevenson, & Bedell, 2017). The latter two modifications will require a use of eye-tracking with the patients with age-related macular degeneration, and necessarily adjustment for calibration, which can be accomplished with a standard eye-tracker set up (e.g. Geringswald et al., 2013; Van der Stigchel, et al., 2013).

## Conclusions

Visual search in the presence of central scotoma could be improved both by efficient and inefficient visual search trainings, leading to faster and more efficient search, suggesting saccadic re-referencing to an extrafoveal retinal location. However, training gains were maximal for the trained type of search and transfer to the other search type was limited. Thus, future research should investigate to what degree the different training methods proposed in the literature lead to benefits in everyday activities like reading or visuospatial tasks that are important for the patients suffering from central vision loss.

*Keywords: age-related macular degeneration, artificial scotoma, foveal vision loss, oculomotor control, oculomotor learning, visual search, attention, peripheral vision, saccadic eye movements, search asymmetries*

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