Transfer of an induced preferred retinal locus of fixation to everyday life visual tasks

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Subjects develop a preferred retinal locus of fixation (PRL) under simulation of central scotoma. If systematic relocations are applied to the stimulus position, PRLs manifest at a location in favor of the stimulus relocation. The present study investigates whether the induced PRL is transferred to important visual tasks in daily life, namely pursuit eye movements, signage reading, and text reading. Fifteen subjects with normal sight participated in the study. To develop a PRL, all subjects underwent a scotoma simulation in a prior study, where five subjects were trained to develop the PRL in the left hemifield, five different subjects on the right hemifield, and the remaining five subjects could naturally choose the PRL location. The position of this PRL was used as baseline. Under central scotoma simulation, subjects performed a pursuit task, a signage reading task, and a reading-text task. In addition, retention of the behavior was also studied. Results showed that the PRL position was transferred to the pursuit task and that the vertical location of the PRL was maintained on the text reading task. However, when reading signage, a function-driven change in PRL location was observed. In addition, retention of the PRL position was observed over weeks and months. These results indicate that PRL positions can be induced and may further transferred to everyday life visual tasks, without hindering function-driven changes in PRL position.

Introduction

Patients with damaged maculae have compromised the part of their visual field with the highest accuracy and sensitivity. Bereft of their main source of information, patients select an alternative and healthy retinal location, which then acts as a pseudofovea and compensates the lack of foveal input. This retinal location is referred to as preferred retinal locus (PRL) for fixation (Cummings, Whittaker, Watson, & Budd, 1985; Fletcher & Schuchard, 1997; Fuchs, 1922; Guez, Le Gargasson, Rigaudiere, & O'Regan, 1993; Mainster, Timberlake, Webb, & Hughes, 1982; Nagel, 1911; Von Noorden & Mackensen, 1962; Schuchard, 2005; White & Bedell, 1990).

In a previous study, we showed that the PRL location can be induced at a specific hemifield when systematic stimulus relocation is applied to a stimulus that evokes saccadic eye movements (Barraza-Bernal, Rifai, & Wahl, 2017). Patients with central scotoma present a strong tendency to develop a PRL in the left side of the visual field (Cummings & Rubin, 1992; Fletcher, Schuchard, Livingstone, Crane, & Hu, 1994; Fletcher & Schuchard, 1997; Sunness, Applegate, Haselwood, & Rubin, 1996); however, in contrast to this observation, other PRL positions were proven to be beneficial for the performance of some visual tasks (Chung, Legge, & Cheung, 2004; Deruaz, Whatham, Mermoud, & Safran, 2002; Frennesson & Nilsson, 2007; Guez et al., 1993; Petre, Hazel, Fine, & Rubin, 2000; Whittaker & Lovie-Kitchin, 1993). For example, a PRL for left-to-right reading will preferentially be below the central scotoma, since only then can the reader estimate the amplitude of the eye movement toward the next word or toward the next line. In this case, a PRL on the left side of the macular scotoma is not convenient and a relocation of the PRL might positively influence the performance of the reading task.

In our previous study, a PRL was induced to be either on the right or on the left hemifield. A stimulus that evoked a saccadic eye movement was always relocated to the induced hemifield when the saccadic location was transferred to the pursuit task and that the vertical location of the PRL was maintained on the text reading task. However, when reading signage, a function-driven change in PRL location was observed. In addition, retention of the PRL position was observed over weeks and months. These results indicate that PRL positions can be induced and may further transferred to everyday life visual tasks, without hindering function-driven changes in PRL position.
eye movement located the stimulus on the opposite hemifield. For example, if the PRL was induced on the left hemifield, and a saccade located the stimulus on the right hemifield, the stimulus was relocated on the left hemifield and vice versa. The relocation was always applied horizontally and had a magnitude of 7.5° of visual angle. The inducement was studied in subjects with normal sight and was performed at early stages of its development. The study showed that systematic stimulus relocations may influence the location in which the PRL developed. Moreover, the training was more effective when the stimulus relocations were in favor of the left hemifield than the right hemifield. However, in everyday life, reactive saccades to appearing targets render only a fraction of occurring eye movements. But, visual impairments affect eye movements in tasks like reading, during locomotion and orientation, and social interaction as well (Trauzettel-Klosinski, 2011). Hence, in reality central vision loss patients are challenged to perform a diversity of visual tasks in their natural environment. Taking this into account, the present study addressed the question whether the PRLs induced in Barraza-Bernal et al. (2017) can be transferred to other important visual tasks. The transfer of the left-induced group, right-induced group, and the group without inducement procedure was analyzed separately using means and standard deviations of the distance between trained and induced group, and the group without inducement. This analysis allowed the determination of potential impact of the inducing procedure on the transfer behavior.

All subjects underwent the PRL training and in 10 of them the PRL location was induced by systematic stimulus relocations. The induced PRL was taken as a baseline and was compared with the PRL used in the new visual tasks. Since PRLs can be trained to enhance the visual performance (Chung, 2011; Sciple, Szlyk, McMahon, Pulido, & Fishman, 2005; Tarita-Nistor, González, Markowitz, & Steinbach, 2009), and since explicit training can improve the variance of the PRL (Kwon, Nandy, & Tjan, 2013), the only comparison parameter that we used was the PRL location.

The everyday life tasks consisted of a pursuit task, a signage reading task, and a text reading task. These tasks were selected to mimic important daily tasks. The pursuit task mimicked object following tasks like cars or any other objects moving in the environment. The signage reading task mimicked the reading of instructional texts, like traffic signs. The text reading task mimicked tasks like reading newspaper or magazines.

The results showed an overall maintenance of PRL location when a pursuit task is evoked. Also for a text reading task, the results showed that the vertical location of the PRL was maintained. However, in the signage reading task, changes in the PRL locations were observed in favor of a functionally driven location selection of PRL.

### Methods

#### Apparatus

The performance of the experiment and of the data acquisition were carried out using a gaze contingent setup based on MATLAB, the Psychtoolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007), the Eyelink toolbox (Cornelissen, Peters, & Palmer, 2002), the Eyelink 1000 Plus eye tracker (SR Research, Ltd., Ontario, Canada), and a VIEWPixx/3D display (VPixx Technologies, Saint-Bruno, Canada) with a vertical refresh rate of 100 Hz and a spatial resolution of 1,920 by 1,080 pixels.

To simulate the central scotoma, a gaze-contingent round mask was presented at the momentary eye position. Scotoma presentation was temporally delayed by less than 20 ms after eye position detection. Vertical and horizontal positions of the right eye were recorded at a spatial resolution of 0.01° and 1 kHz while the left eye was patched.

A chin rest was used to stabilize the head and to locate the eyes at a distance of 62 cm from the display.

#### Participants

Fifteen participants took part in the study, five males and 10 females aged between 24 and 33 years (mean: 26.6 years). Every participant had a developed PRL, acquired under simulation of central scotoma after four training sessions (Barraza-Bernal et al., 2017). Five participants had a PRL induced in the left hemifield; five different subjects had a PRL induced in the right hemifield. The remaining five subjects had a PRL developed without any inducement procedure.

The study was performed in accordance with the Declaration of Helsinki. Subjects signed an informed consent before their participation. All subjects were eye healthy and had normal or corrected-to-normal visual acuity.

#### Study design

Figure 1 shows the sequence of experiments performed on the study. The gray box represents the training that subjects performed prior to the performance of this experiment (Barraza-Bernal et al. 2017). To develop a PRL, subjects underwent a visual task in which a single saccade target was presented at a time.
The black boxes represent the experimental blocks performed in this study. In Session 1, the transfer of PRL was studied. The experiment started with a baseline measurement of the PRL location developed after training. These data were identical to the Final Performance Assessment data presented in Barraza-Bernal et al., 2017. The PRL location obtained in this measurement was used as a baseline for comparison with the PRL used in the performance of the three everyday life visual tasks. The baseline PRL position was acquired using a single appearing stimulus that evoked a saccade. Consecutively, subjects performed the three visual tasks under simulation of central scotoma: a pursuit task, a signage reading task, and a text reading task. These measurements were performed right after the end of the training. Thereafter, the retention of the developed PRL location was determined in two separate sessions. Two sessions at different points in time after the performance of Session 1 were recorded. The first retention was acquired between six and seven weeks after the performance of Session 1. Every subject participated in this session. The second retention was a long-term retention measurement, taken 11 and 25 months after the performance of Session 1. Five subjects were available for the performance of these sessions.

Stimuli and procedure

All experiments were performed in a dark room. The simulation of the central scotoma consisted of a foveally presented circular scotoma spanning ±3° of visual angle. The color of the scotoma was dark gray whereas the background color was light gray. The luminance of the light gray screen was 64 cd/m².

At the beginning of any phase of the experiment a 13-point calibration was performed. This calibration collected fixation samples from 13 known target points to map raw eye data to gaze position. Subsequently, a validation with 13 points was performed, which provided information about the calibration’s accuracy.

The experiments continued only if the eye tracker qualified the validation to be good.

Baseline

In Session 1, all subjects had to perform a visual task previous to the first task to determine their baseline PRL location.

The baseline PRL location was determined with stimuli identical to the PRL training. Saccade stimuli were presented at random locations on the screen and subjects had to perform a visual task in a set of four blocks. Figure 2 shows examples of the stimuli presented in each block. In the first block, a group of colored discs were shown and subjects had to identify red among blue discs in a five-color stimulus. In the
second block, a group of lines and squares were shown and subjects had to report whether there were more or less squares than lines in a five-component stimulus. In the third block, horizontal and vertical lines were shown and subjects had to report whether there were more or less horizontal than vertical lines in a five-component stimulus. Finally, in the fourth block, three letters at the center of the screen and four letters at each corner of the screen were shown. In a comparison task, subjects had to find in one of the four corners the letter that was not presented in the center. The overall stimulus size was 1.7×1.7° of visual angle. In every block the eye movement data were acquired for 1.5 min; however, the total duration of the experiment was different for every subject because drift corrections were performed between the trials.

The PRL location obtained after the performance of this task was later used to compare the PRL location used under the performance of the everyday life visual tasks.

**Task 1: Performance of pursuit eye movements**

Figure 3 shows an example of the task. Under simulation of central scotoma, subjects had to pursue a group of discs moving with a random trajectory over the screen at a speed that varied between 15°/s and 25°/s. The discs had always the same distance relative to each other; only the mean position changed over the screen. All the discs had different diameters. Overall, the stimulus spanned 1.7×1.7° of visual angle. At the beginning of a trial, every disc was black, but while the group of discs was moving on the screen, the discs changed their color at randomly selected times and locations. The colors varied between yellow, blue, magenta, cyan, green, and red. The task was to press the space key when the disc located at the center turned red. Afterward, the discs turned black again and a new trial started. Eye movement data were acquired for 3 min.

**Task 2: Performance of signage reading task**

Figure 4 shows examples of the signage reading task. Subjects had to read three words. The group of words covered 1.5×16° of visual angle and were composed of similar letters (e.g., WANT WENT WELL). The words were presented until the subject reported successful reading; thus, subjects were free to read for the time that they estimated necessary. Subjects were asked to read the words with the central scotoma and press the space key to report successful reading. Subsequently, without central scotoma simulation, two sets of three words were presented, and subjects were asked to find the string of words shown previously among these two alternatives and press the up or down key to report the answer.
Task 3: Performance of text reading task

Figure 5 shows an example of the text reading task. Subjects had to read a text under simulation of central scotoma for the time that they estimated necessary. The text was presented in five subsequently shown paragraphs. Each paragraph consisted of six lines. The paragraph was aligned to the left and every line had a different length. The paragraph extended $33\frac{8}{8}$ of visual angle horizontally and was positioned centrally on the screen.

As resolution of retinal areas located more than $3\frac{8}{8}$ of visual angle away from the fovea is decreased, the character size of the text was magnified. Chung et al. (1998) showed that the critical print size for $3\frac{8}{8}$ eccentricity, in which reading speed is not limited by print size, is approximately $0.5\frac{8}{8}$. Therefore, to avoid limitations on reading speed due to print size, the character size of our reading task was $0.5\times0.7\frac{8}{8}$ of visual angle. The spacing between lines was $1.9\frac{8}{8}$ of visual angle. The subject had to read the text of the five paragraphs and once finished reading, answer questions about its content. The questions were performed verbally and they had to be answered with a yes or a no.

Retention of the developed PRL

For a fair comparison between the current PRL position and the baseline PRL position, retention was assessed by performing tasks already performed before. In the retention session performed six to seven weeks after Session 1, the same experiment performed in the assessment of the baseline PRL was followed, but here the duration of data acquisition was 5 min.

Data analysis

Position of the PRL for saccade stimulus and smooth pursuit eye movements

Eye movement data were classified using the eye tracker internal algorithms. The algorithm classified saccades, fixation, and blinks using a saccadic velocity threshold of $30\frac{8}{8}$/s, a saccadic acceleration threshold of $8,000\frac{8}{8}$/s$^2$, and saccadic motion threshold of $0.1\frac{8}{8}$. This allowed the capture of smooth pursuit eye movements under the category of fixations, as the speed of these eye movements under a simulated scotoma is typically below $25\frac{8}{8}$/s (Aguilar & Castet, 2011), and the speed of the stimulus was also always in the range of $15\frac{8}{8}$/s and $25\frac{8}{8}$/s. The eye movement data were translated to maps that summarized the fixational behavior after the performance of each experimental task. They show the location of the stimulus relative to the simulated scotoma after the performance of the task. The maps were obtained by calculating the stimulus position relative to the center of scotoma for every fixation recorded in the experiment. Subsequently, a bivariate Gaussian kernel estimator (Botev, Grotowski, & Kroese, 2010) was used to calculate the density of the fixation maps. The position of the PRL was defined to be the point located at the highest density of the fixation map (Kwon et al., 2013).

This analysis was used in the baseline PRL assessment, smooth pursuit eye movements, signage reading task, and retention. Figure 6 shows an example of a fixation map after density calculation. The gray center represents the area covered by the scotoma and the cross at the highest density of the fixation map represents the PRL location.
Radius of baseline PRL

The radius of the baseline PRL was based on the Euclidean distance between the baseline PRL location and every gaze position under fixation in the baseline task. The distance representing the 68th percentile of all measured gaze position distances from the baseline PRL location was defined to be the radius of the baseline PRL.

Distance between baseline PRL and transferred PRL

The distance between the baseline PRL and the transferred PRL was calculated using the Euclidean distance between both PRL locations.

Quantity for the transfer of the PRL

To quantify the PRL transfer, a Transfer Ratio $R_T$ was introduced. $R_T$ was calculated by dividing the distance between the PRLs $PRL_d$ over the radius of the baseline PRL $R_B$, as shown in Formula 1.

$$R_T = \frac{PRL_d}{R_B} \quad (1)$$

$R_T$ values below 1 indicate that the transferred PRL was located within the radius of the baseline PRL extend, whereas $R_T$ values above 1 indicate that the transferred PRL was not located within the radius of the baseline PRL extend.

Position of the PRL for text reading task

In the text reading task, we adapted a method used by Timberlake, Peli, Essock, & Augliere (1987) to determine the location of the PRL. They divided the retina into several perceptual areas, forming a grid to determine the location of the PRL. They calculated the percentage of words hitting every area and defined the PRL to be at the area with the highest percentage. In our study, the grid was transformed to a radial perceptual grid with a size that spanned the visual perceptual area for reading.

For people with normal sight, the minimum reading perceptual area covers 2° of visual angle to the right and to the left sides of the fixation and 1° of visual angle above and below the fixation (Aulhorn, 1953). The total perceptual span, or region of effective vision during eye fixations in reading, is known to be larger on the right side of the fixation point (Rayner, Slattery, & Bélanger, 2010). In this study, since the letters were magnified to ease the performance of the reading, we estimated the perceptual span window to be 3.7° of visual angle.

Figure 7, panel A shows the radial grid with a visual span out of the scotoma of 3.7° of visual angle. In the analysis, the center of the grid was aligned at each fixation and the centroid of any letter that was lying within this grid, was saved as a reference stimulus position, Figure 7, panel B. In panel C can be seen an example of the radial grid after the collection of all fixations.
centroids for all fixations. Panel D shows the percentage of hits per radial block for the example presented in panel C. Additionally, the red dot in panel D shows the baseline PRL position for that sample subject.

Results

Baseline: Acquisition of PRL location

Prior to this study, 10 out of 15 subjects developed a PRL that was induced using systematic stimulus relocations; the other five subjects had a PRL developed without an inducement procedure (Barraza-Bernal et al., 2017). The baseline PRL position was acquired from fixation during the four saccade tasks. The position of highest fixation density was defined as the PRL location. Figure 8 shows the baseline PRL locations of every subject from left-induced PRL (blue squares), right-induced PRL (red squares), and not induced PRL (black diamonds) groups, which also correspond with the final performance assessment presented in Barraza-Bernal et al., 2017. These baseline PRL locations were compared with the PRL locations used during everyday life visual tasks.

Figure 8 shows that all but two subjects developed a PRL outside of the scotoma. Subjects 12 and 13 alternated the fixations between two locations (inside and outside of the scotoma) suggesting that right-induced PRLs may be more difficult to develop.

Transfer of PRL to smooth pursuit eye movements

The smooth pursuit fixation maps for every subject are shown in Figure S1. The PRL location was compared with the baseline PRL location. Figure 9A shows bars that represent the radius of the baseline PRL, which was defined to be the 68th percentile of the distances obtained between the baseline PRL location and every gaze point during fixation. The black dot represents the Euclidean distance between baseline PRL and transferred PRL. This is shown for all subjects. The groups are distinguished by colors, where blue corresponds with the left-induced group, red to the right-induced group, and gray to the naturally developed PRL group. A black dot within the bar indicates that the transferred PRL is located within the radius of the baseline PRL extend. For subject number 5, the mean radius of baseline PRL was large because the subject developed two PRLs, one above the scotoma and another one below the scotoma. The mean distance between baseline PRL and pursuit PRL positions for all subjects from the left-induced group was 0.97 ± 0.26° of visual angle, and for the subjects from the right-induced group was 1.55 ± 1.35° of visual angle.

The mean Transfer Ratio RT was calculated by dividing the distance between the PRLs over the radius of the baseline PRL. RT was 0.29 ± 0.06 for the left-induced group, 0.49 ± 0.55 for the right-induced group, and 0.57 ± 0.43 for the subjects without the inducement procedure. The RT values obtained for all subject are significantly smaller than one (one sample t test, t(14) = −5.3, p < 0.01). Thus, the results suggested a transfer from saccadic task to smooth pursuit eye movements.

Figure 9B shows the PRL location for the pursuit task connected to their corresponding baseline PRL position for the three groups and illustrates the transfer

Figure 9. (A) Radius of the baseline PRL for every subject (bars) and the distance between the pursuit PRL and the baseline PRL (black dot). (B) PRL position for the pursuit PRL connected to the baseline PRL position (black dot) for the three groups.
of the PRL, as well as the maintenance of the induced hemifield.

In Barraza-Bernal et al., 2017, subjects 12 and 13 alternated the fixations between inside and outside of the scotoma. This behavior suggested that right-induced PRLs may be more difficult to develop. However, Figure 9B shows that the subjects brought the PRL from the scotoma region to a location out of the scotoma, indicating a further progression of PRL development. Subjects without the inducement procedure showed a mean distance between baseline PRL and pursuit PRL of 1.46 ± 1.44° of visual angle and only one subject showed a pursuit PRL located out of the radius of the baseline PRL (subject 1). Thus, PRLs induced under a saccadic evoking paradigm transfer to a pursuit task.

Transfer of PRL to reading task

**Signage reading task**

Figure 10A shows bars representing the radius of the baseline PRL together with a black dot that represents the distance of the signage reading PRL to the baseline PRL. The mean distance between the baseline PRL and the signage reading PRL for the subjects from the left-induced group and the right-induced group were 3.57 ± 1.78° of visual angle and 1.62 ± 1.11° of visual angle, respectively. Subjects from the control group showed a mean distance between baseline PRL and signage reading PRL of 2.8 ± 1.88° of visual angle.

The mean Transfer Ratio \( R_T \) for the left-induced group was 1.05 ± 0.50, for the right-induced group was 0.42 ± 0.27, and for the subjects without the inducement procedure was 2.02 ± 3.08. Additionally, the \( R_T \) values obtained for all subject were not significantly smaller than one (one sample \( t \) test, \( t(14) = 0.36, p = 0.72 \)). This suggested a general lack of PRL transfer for this task. The PRL positions change may be a change based on a functionality driven selection mechanism.

Figure 10B shows the PRL location for the signage reading connected to their corresponding baseline PRL position for the three groups and confirm that subjects from the left-induced group changed the PRL from the left hemifield to a point below the scotoma.

Figure 10B suggests that subjects locate the PRL inside the scotoma. But, considering the size of the stimulus, the pattern rather shows that the subjects placed the text as centered as possible. At the chosen positions, the size of the stimulus was big enough to leave one part of the letters visible. One example text position is shown in Figure 11. It demonstrates that a portion of the letters is visible.

**Text reading task**

The mean fixation duration of all subjects ranged between 212 and 314 ms and overall, the mean time spent during fixations was 272 ± 33 ms.

The percentage of hits per radial block was plotted together with the baseline PRL for every subject in Figure 12.

Due to the distribution of words on the left and right of the scotoma, the exact fixated word is unknown; thus, only the vertical position of a PRL is assessable. Therefore, we compare these results to the baseline vertical position.

To distinguish between PRLs located above versus below the scotoma, the perceptual window was divided

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Figure 11. Example of a subject with a PRL location seemingly inside the scotoma. The example shows blue crosses corresponding with the center of mass of each word. When the center of mass of the word on the center is located at the PRL position, a portion of the word is still visible and can be used for the performance of the task.
into four quadrants as shown in Figure 13. Quadrants 2 and 4 were contrasted, leaving the influence of the words that were located on the left or right side of the scotoma unconsidered (quadrants 1 and 3). The total percentage of hits in quadrant 2 $P_{Q2}$ and quadrant 4 $P_{Q4}$ were calculated and subsequently, the ratio $R$ (Equation 1) was calculated.

$$R = \frac{P_{Q2} - P_{Q4}}{P_{Q2} + P_{Q4}} \quad (1)$$

This ratio classified the position of the PRL in terms of up or down; every value above 0 corresponded with a PRL located above the scotoma; and every value below 0 corresponded with a PRL located below the scotoma.

Figure 14 shows the ratios for every subject (unfilled). For comparison, the vertical location of the baseline PRL is presented for each subject (filled). The diagrams show that subjects kept their PRL position close to the baseline position. Furthermore, all but two subjects (subject 6 and subject 1) maintained their vertical PRL location. This suggests that the vertical location of the PRL is maintained in a text reading task.

### Retention of the PRL position

#### Short-term retention

**Short-term retention of saccadic behavior:** The retention was tested six to seven weeks after the initial PRL development. Figure 15A shows bars representing the radius of the baseline PRL together with a black dot that represents the distance of the retention-saccade PRL to the baseline PRL. The mean distance between baseline PRL and saccade PRL for the subjects from the left-induced group was $2.19 \pm 1.77^\circ$ of visual angle, for the subjects from the right-induced group it was $1.47 \pm 1.42^\circ$ of visual angle. The mean distance between baseline PRL and retention PRL for the subjects without an induced PRL was $0.92 \pm 0.98^\circ$ of visual angle.

The mean Transfer Ratio $R_T$ for the left-induced group was $0.67 \pm 0.54$, for the right-induced group was $0.36 \pm 0.18$, and for the subjects without the inducement procedure was $0.32 \pm 0.21$. The $R_T$ values were significantly smaller than one (one sample $t$ test,
This suggested a transfer of PRL.

Figure 15B shows the PRL location for the retention-saccadic task connected to their corresponding baseline PRL position for the three groups and confirm a general retention of PRL and also a maintenance of the induced hemifield.

Figure 15B also shows that three subjects presented fixations inside the scotoma, two from the left-induced group, and one from the right-induced group. The two subjects from the left-induced group seemed to lose their developed PRL and moved it to the center of the scotoma whereas the subject from the right-induced group had a baseline PRL inside the scotoma. In these cases, the subjects alternated the fixations between their baseline PRL location and the center of the scotoma. Figure 16 shows the fixations for both subjects (subjects 6 and 7) that were alternated between the PRL and the center of the scotoma, suggesting that the induced PRL was partially retained. Only for comparison, two subjects that retained the PRL are shown below (subjects 4 and 15).

Short-term retention of pursuit eye movements: Figure 17A shows bars representing the radius of the baseline PRL together with a black dot that represents the distance of the retention-pursuit PRL to the baseline PRL. The mean distance between the baseline PRL and pursuit PRL was $1.26 \pm 0.89^\circ$ of visual angle in the left-induced group. In the right-induced group it was $2.21 \pm 1.52^\circ$ of visual angle. The subjects without an induced PRL showed a mean distance between the baseline PRL and pursuit PRL of $1.30 \pm 1.33^\circ$ of visual angle.

The mean Transfer Ratio $R_T$ for the left-induced group was $0.38 \pm 0.27$, for the right-induced group was $0.65 \pm 0.43$, and for the subjects without the inducement procedure was $0.55 \pm 0.52$. Additionally, the $R_T$ values obtained for all subject were significantly smaller than one (one sample $t$ test, $t(14) = -4.52$, $p < 0.01$), suggesting a transfer of PRL.

Moreover, Figure 17B shows the PRL location for the retention-pursuit task connected to their corresponding baseline PRL position for the three groups.

Figure 14. Ratio quantifying the vertical location of the PRL for text reading (unfilled points) and vertical location of the baseline PRL (filled points). Values above the zero line correspond with PRLs located on the upper visual field and values below the zero line to PRLs located on the lower visual field.
and confirms the retention of the PRL as well as the maintenance of the induced hemifield.

The same subjects that brought the PRL to a location outside of the scotoma in the pursuit task, kept the pursuit PRL six to seven weeks after the task performance. These results showed retention of both left- and right-induced PRLs and suggest that inducing procedures using saccadic evoking tasks have long-lasting effects.

**Long-term retention**

A total of five subjects were recruited for the measurement of long-term retention, one from the left-

induced group, two from the right-induced group, and two subjects with a freely developed PRL. The two subjects from the right-induced group were recruited 11 months after the performance of Session 1. The subjects from the left-induced group and not induced PRL were recruited 25 months after the performance of Session 1. Figure 18A shows bars representing the radius of the baseline PRL together with a black dot that represents the distance of the long-term retention PRL to the baseline PRL. The distance between baseline PRL and retention PRL for the subject from the left-induced group was 1.12° of visual angle, whereas the mean distance between baseline PRL and retention PRL for the two subjects from the right-induced group was 0.61 ± 0.15° of visual angle. The two subjects with a self-chosen PRL showed a mean distance between the baseline PRL and long-term retained PRL of 0.84 ± 0.04° of visual angle.

The **Transfer Ratio** $R_T$ for the subject from the left-induced group was 0.34, for the both subjects from the right-induced group was 0.16 ± 0.02 and for both subjects without the inducement procedure was 0.69 ± 0.58. Additionally, the $R_T$ values obtained for all subject were significantly smaller than one (one sample $t$ test, $t(4) = -3.33$, $p = 0.02$). This showed that even years after PRL development, some subjects retained the PRL.

**Discussion**

The way that individuals position their eye during eccentric fixation has been studied under different oculomotor visual tasks, for example, walking, doing sports, or making sandwiches and tea. Fixation locations are shown to optimize performance with respect to the spatio-temporal demand of the task (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Land & Lee, 1994; Land & Furneaux, 1997; Land, Mennie, & Rusted, 1999; Turano, Geruschat, & Baker, 2003).
Already Yarbus’ work (1967) revealed the intrinsic cognitive nature of eye movements and demonstrated the importance of the instructions in the determination of fixation location during the passive inspection of visual scenes. These specific patterns of eye movements were also reported to be idiosyncratic (Andrews & Coppola, 1999) and suggest that fixational behavior during active visual tasks, like reading or visual search, differs from that during the performance of a passive inspection of a visual scene. In this study, PRL positions were studied under the performance of different visual tasks: pursuit, signage reading, and text reading.

The first visual task was pursuit eye movements. Pursuit depends on a number of stimulus parameters. Target luminance, size, and position on the visual field can influence the latency and gain of pursuit (Westheimer & McKee, 1975). Also, pursuit ensures optimal vision only when the target is moving slowly since the visual acuity starts to decrease when the retinal image velocity exceeds 3°/s (Westheimer & McKee, 1975). Furthermore, when the amplitude or frequency of the target is increased, the smooth moving eye starts to lag behind the target and its velocity becomes smaller (Collewijn & Tamminga, 1984; Fuchs, 1967; Yasui & Young, 1984). All these influential parameters may have tuned the induced PRL location; however, our results showed a transfer of induced PRL to pursuit PRL. Furthermore, induced PRLs were maintained at their induced location. In two cases, the PRL was moved outside of the scotoma, which suggested that the pursuit task may be facilitating the performance of the eccentric fixation.

Our data also supports other studies that already demonstrated a fast and consistent oculomotor adaptation to a simulated central scotoma under pursuit eye movements (Pidcoe & Wetzel, 2006). Furthermore, it is known that the neuronal substrate of pursuit and saccades differ strongly. Nonetheless, transfer of PRLs induced by saccadic training to pursuit tasks was shown.

The second task tested was reading. Also in this task, a variety of influencing factors exist. When reading a text or paragraph, the eye movements are affected by the syntax of the sentence (Rayner & Pollatsek, 1987) and the complexity of the words of interest (Pollatsek, Rayner, & Balota, 1986; Zola, 1984). These sets of visual parameters may influence even more significantly the visual behavior at the presence of the central scotoma.

Timberlake et al. (1987) examined fixation patterns in patients with macular scotoma and reported that a single retinal area was used for reading words composed of three letters, but when some of the patients were instructed to use another alternative region for fixation, there was a small improvement on reading speed. This suggested that the PRL used during signage reading might not be the best for reading a text. We investigated signage reading and found that the subjects from the left-induced group did not transfer the PRL position. Some showed central fixation and a distance between the signage reading and the baseline PRLs that were out of the baseline PRL range. These changes hint toward difficulties to transfer the PRL into the word reading task and must be taken into account on the development of training procedures.

Moreover, some subjects changed the PRL location from the left side of the scotoma to a position below the scotoma. This result supports that a PRL for left-to-right reading will preferentially be below the central scotoma (Chung et al., 2004; Deruaz et al., 2002; Frennesson & Nilsson, 2007; Guez et al., 1993; Petre et al., 2000; Whittaker & Lovie-Kitchin, 1993). However, this effect was observed on both induced PRL and naturally developed PRL.

The subjects from the right-induced group kept a distance between signage reading and baseline PRL always within the range of baseline PRL radius; however, unlike in the pursuit task, the subjects located induced and naturally developed PRLs in the periphery of the visual field. This suggests that the subjects may have been using a different strategy for reading text.
the reading PRL mainly on the scotoma. This can be attributed to the size of the letters. Eccentric fixations left a portion of the letters visible and maybe subjects used this portion for the performance of the task.

Another possible explanation is a noisy control of the eye movements that may be attributed to the different conditions in which the scotoma was simulated or to the different inducing paradigms. In Barraza-Bernal et al. (2017) we controlled the oculomotor change by means of a PRL value. The analysis showed that subjects from left-induced group and subjects without an a PRL inducement improved the fixation behavior significantly after three training sessions; nevertheless, subjects from the right-induced group did not show a significant improvement of oculomotor behavior. Perhaps, this deficit on oculomotor control was the factor reflected on the signage reading task.

We investigated text reading and found that all but two subjects maintained their vertical PRL location. Two subjects showed changes on their vertical location; these were the same subjects that did not transfer their PRL to signage reading. The maintenance of vertical position may suggest a transfer of baseline PRL to text reading.

 Seventy percent of the subjects presented a Ratio R below 0, indicating a vertical PRL location situated below the simulated scotoma. These results again support that PRLs for left-to-right reading are preferentially below the scotoma.

In normal reading, the fixation duration occurs during an average time between 200 and 250 ms (O’Regan, 1980; Sereno & Rayner, 2003). In the text reading task, subjects used a longer average information-processing time of 272 ± 33 ms. This might be attributed to the decrease of visual acuity that makes it harder to identify words presented in parafoveal regions.

We also investigated the retention of the learned behavior. When saccadic behavior was tested six to seven weeks after the first session, we observed that all but two subjects kept the PRL in a region within the baseline PRL. This result suggests that PRLs can be maintained for weeks without simulation. Specifically, the induced locations maintained, suggesting that the PRL position was successfully induced. The retention was also tested with a pursuit task and we observed that all but two subjects maintained their PRL location and in addition, all PRL locations observed were consistent with the induced PRL location. The two subjects that changed their PRL moved it to eccentric locations, suggesting that the pursuit movements might facilitate the performance of eccentric fixations.

Additionally, we investigated retention of the saccade task in five subjects after 11 months and 25 months. Every subject retained the PRL and kept the induced PRL location. Kwon et al. (2013) also showed retention in periods of time between one week and one month. In our study we showed an unreported and longer period of retention. These long-lasting effects suggest that the learned behavior can be considered permanent.

Regarding the number of PRLs, only one of 15 subjects showed a development of two eccentric PRLs, which corresponds to the 6% of the subjects tested. In contrast, other studies on patients showed that a larger portion used more than one PRL during a simple fixation task (39% in Whittaker, Budd, & Cummings, 1988; and 44% in Crossland, Culham, Kabanarou, & Rubin, 2005). The main difference between the numbers of PRLs used may be attributed to the size of the scotoma. Crossland et al. (2005) showed that multiple PRLs were more likely to occur if the scotoma size exceeded 20° and attributed this to a decrease of fixation stability when the target is presented at such a large eccentricities of the fovea.

The results presented can be summarized as follows: The induced PRL transferred to the pursuit eye movement PRLs and to the vertical component of the text reading PRLs. However, the induced PRL was not transferred to the signage reading PRLs. The induced PRLs were retained after a short period of time (six to seven weeks) under the performance of pursuit eye movements and saccadic eye movements. For every subject available, the induced PRLs were also retained after a long period of time (one to two years) under the performance of saccadic eye movements. However, since only five subjects were recruited after such long time period, the conclusions on the long-term retention are limited.

Although the present results provide first evidence on a selective transfer behavior of eccentric fixations, the reality of patients with central scotomas differs from the simulated conditions in a variety of ways. Laboratory conditions do not represent everyday life situations of patients with maculopathies in all its detail. Furthermore, performance is an important indicator for final training success in real life conditions. Thus, further studies might focus on the evaluation of task performance in a broad variety of tasks, as well as on the transfer of the presented findings to clinical training procedures.

**Conclusion**

We show a maintenance of PRL location when pursuit eye movements were evoked. Furthermore, we show a vertical maintenance of PRL location when text reading was performed. In signage reading, PRL positions were adjusted to the low demand of the task, allowing part of the stimulus to be covered by the
scotoma. In addition, the retention of the trained PRL was studied weeks and months after the last training procedure and subjects showed a retention of their PRL, both for induced and freely chosen PRL positions.

Thus, learned behavior can be transferred to an untrained visual task. This allows the training of specific visual tasks using other alternative visual tasks. For example, reading efficiency may be improved using saccade-evoking tasks. However, we showed that in some cases PRLs are still subject to the demand of the task, suggesting that trained PRLs do not prevent other selection mechanisms to change the PRL location. Thus, the trained PRL can be considered as a starting point to enhance the visual performance.

Keywords: induced preferred retinal locus, oculomotor learning

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References


