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Consistency of preferred retinal locus across tasks and participants trained with a simulated scotoma

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Abstract

After loss of central vision following retinal pathologies such as macular degeneration (MD), patients often adopt compensatory strategies including developing a “preferred retinal locus” (PRL) to replace the fovea in tasks involving fixation. A key question is whether patients develop multi-purpose PRLs or whether their oculomotor strategies adapt to the demands of the task. While most MD patients develop a PRL, clinical evidence suggests that patients may develop multiple PRLs and switch between them according to the task at hand. To understand this, we examined a model of central vision loss in normally seeing individuals and tested whether they used the same or different PRLs across tasks after training. Nineteen participants trained for 10 sessions on contrast detection while in conditions of gaze-contingent, simulated central vision loss. Before and after training, peripheral looking strategies were evaluated during tasks measuring visual acuity, reading abilities and visual search. To quantify strategies in these disparate, naturalistic tasks, we measured and compared the amount of task-relevant information at each of 8 equally spaced, peripheral locations, while participants performed the tasks. Results showed that some participants used consistent viewing strategies across tasks whereas other participants’ strategies differed depending on task. This novel method allows quantification of peripheral vision use even in relatively ecological tasks. These results represent one of the first examinations of peripheral viewing strategies across tasks in simulated vision loss. Results suggest that individual differences in peripheral looking strategies following simulated central vision loss may model those developed in pathological vision loss.

1. Introduction

Macular degeneration (MD), a progressive pathological condition affecting central vision, represents one of the leading causes of blindness in western countries, with statistical projections indicating that by 2040, 248 million people worldwide will have some form of macular degeneration (Wong et al., 2014). Late-stage MD often results in a dense, central region of blindness (retinal scotoma) corresponding to up to 20° of the visual field. MD has dramatic effects on everyday life activities like reading and recognizing faces, greatly affecting patients’ independence and resulting in limitations to autonomy and high levels of dependence on others (Williams, Brody, Thomas, Kaplan, & Brown, 1998). Loss of vision and autonomy take a toll on these patients’ quality of life (Šiaudvytyte, Mitkute, & Balčiuniene, 2012; Taylor, Hobby, Binns, & Crabb, 2016). As a spontaneous form of coping, MD patients tend to autonomously develop compensatory strategies, often in the form of eye

movement patterns oriented towards a portion of the retina outside of the scotoma, referred to as “preferred retinal locus” (PRL). Indeed, adoption of a PRL to replace the fovea in visual tasks seems to be one of the more common oculomotor strategies observed in MD patients (White & Bedell, 1990).

However, the exact mechanisms behind PRL development are still elusive. Several factors seem to contribute to it, such as attention resources at different retinal locations (Barraza-Bernal et al., 2017), proximity to the fovea/border of the scotoma (Cheung & Legge, 2005), while residual visual acuity seems to be less critical (Bernard & Chung, 2018). Moreover, some patients seem to switch across different PRLs depending on the lighting conditions, the stimulus, or the task they are performing (Altpeter, Mackeben, & Trauzettel-Klosinski, 2000; Duret, Issenhuth, & Safran, 1999; Lei & Schuchard, 1997; Safran, Duret, Issenhuth, & Mermoud, 1999) suggesting a goal-based element in PRL selection. Cheung and Legge (2005) proposed three possible mechanisms guiding the selection of a PRL: 1) *function-driven selection,* in which the PRL is determined by the nature of the visual task, for example a PRL in the lower visual field is preferable for reading; 2) *performance-driven selection*, in which the PRL gets chosen in a the healthy portion of the peripheral retinal location with the highest visual acuity or in regions with high attentional performance; and 3) *retinotopy-driven selection,* in which the location of the PRL might be a consequence of reorganizations of retinotopically mapped cortical regions, where, for example, deafferented V1 neurons spontaneously remap so that they receive inputs from retinal locations near the scotoma. However, there seems to be evidence against each one of these as the sole explanation for PRL development: for example, there is evidence that some patients have higher visual acuity outside the PRL (Bernard & Chung, 2018) and the very existence of cortical reorganization in the lesion projection zone of the deafferented fovea is still debated (Baseler et al., 2011; Dilks, Baker, Peli, & Kanwisher, 2009; Masuda, Dumoulin, Nakadomari, & Wandell, 2008).

Understanding the mechanisms behind PRL development would not just provide insights on the way the visual system spontaneously reorganizes following large-scale deafferentation but would also pave the way for developing more appropriate rehabilitative strategies aimed at teaching patients to develop a stable PRL. Indeed, MD patients who successfully develop a PRL can take months to do so, while others fail to do so altogether (Crossland, Culham, Kabanarou, & Rubin, 2005).

In recent years, studies addressing the mechanisms of PRL development have used a simulated scotoma framework, a controlled model of central vision loss in which healthy individuals are trained to perform a visual task while a gaze-contingent display, controlled by a high-resolution eye tracker, systematically occludes their central vision (Barraza-Bernal, Ivanov, et al., 2017; Barraza-Bernal, Rifai, & Wahl, 2017; Kwon, Nandy, & Tjan, 2013; Liu & Kwon, 2016; Maniglia, Jogin, Seitz, & Maniglia, 2020; Maniglia, Visscher, & Seitz, 2020; Walsh & Liu, 2014). Studies using this approach showed that participants exhibit oculomotor behaviors normally observed in clinical populations, often after only few hours of exposure to the simulated scotoma, unlike the several months that seem necessary to MD patients to develop a stable PRL (Crossland, Culham, Kabanarou, & Rubin, 2005).

Few studies have looked at the extent to which the PRL developed during the simulated scotoma training transferred between visual tasks. Recently, Barraza-Bernal, Rifai, and Wahl (2017b) showed PRL location retention between the trained task and three transfer tasks, namely signage reading, smooth pursuit and reading. Specifically, results showed that the PRL location was maintained in the smooth pursuit task, the vertical location of the PRL was preserved in the reading task while in the signage reading task, the PRL location was adjusted to the lower demand of the task, allowing part of the stimulus to be covered by the scotoma).

However, no study so far has systematically compared PRL location across tasks. Here, we looked at consistency of PRL use across tasks and participants in conditions of simulated central vision loss, with the goal of understanding, 1) whether, at the group level, participants show an overall bias towards selecting specific regions of the periphery of the visual field across task; and 2) whether tasks showed a consistent pattern of peripheral visual field use across participants.

2. Materials and methods

2.1. Participants

Nineteen healthy participants (mean age: 20.4 ± SD 1.8 years; 12 females, 7 males) with normal or corrected-to-normal vision were recruited at the University of California at Riverside to take part in the study. Experimental protocols were approved by the Human Research Review Board of the University of California at Riverside, and all participants gave written informed consent prior to the experiment.

In this paper, we focus on oculomotor differences in a series of assessment tasks, while in a previous paper (Maniglia, Jogin, Visscher and Seitz, 2020) we characterized oculomotor behavior during training with simulated central vision loss in the same sample of participants. Thus, detailed information on participants and methods can be found in Maniglia et al. (2020).

2.2. Stimuli and apparatus

Details on stimuli and apparatus can be found in Maniglia, Jogin, Visscher and Seitz (2020). In brief, participants' eye movements were monitored monocularly using an infrared video-based eye tracker sampled at 500 Hz (EyeLink 1000 Plus Tower Mount, SR Research Ltd., Ontario, Canada) using drift correction. Calibration was performed at the beginning of each session. A digital-to-analog converter (Bits++; Cambridge Research Systems, Rochester, UK) was used to increase the dynamic contrast range (10-bit luminance resolution). A 10-bit gamma-corrected lookup table was used to linearize the luminance of the monitor. The luminance of the simulated scotoma was 11% higher than the luminance of the background display, amounting to 50% (127 RGB) and 39% (100 RGB) of the maximum screen luminance, respectively. Visual stimuli were generated using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and EyeLinkToolbox (Cornelissen, Peters, & Palmer, 2002).

2.3. Procedure

Throughout the study, participants performed a series of tasks in conditions of simulated central vision loss, rendeded through a gaze-contingent scotoma (opaque disc obstructing the central 10° of each participant's visual field). Sessions 1 and 2 were used to familiarize people with the use of peripheral vision (PRL induction procedure, see below for details). Sessions 4 through 13 constituted the perceptual learning training (see below for details). Sessions 3 and 14 included a series of assessment tasks measuring visual acuity, visual search and reading abilities. Sessions lasted on average 45 minutes. Figure 1 presents a layout of the study procedure.

2.3.1. PRL induction—During session 1 and 2, participants underwent one of two types of PRL induction: either the assigned PRL or the annulus induction. See Maniglia, Jogin, Visscher and Seitz (2020) for details. While the use of different induction procedures was to test whether different methods may lead to systematically different oculomotor behaviors, the large variability within conditions precluded significant conclusions with the current sample size. Thus, analyses were conducted over the whole sample.

2.3.2. Visual acuity—In sessions 3 and 14, the pre-test and post-test, participants performed a visual acuity task aimed at measuring visual performance and oculomotor strategies in a transfer task. At the beginning of each trial, participants were presented with a central rectangle slightly larger than the artificial scotoma and asked to center their gaze so the scotoma would be within the boundaries of the rectangle. Then, a Landolt C, in the Sloan font (Pelli, Robson, & Wilkins, 1988) and at 100% luminance (255 RGB), appeared at a random location, anywhere on the screen, and participants were asked to report its orientation (C opens up, down, left, or right). The size of the letter C was initially 2° and progressively increased (or decreased) following correct (or incorrect) responses according to a 3:1 staircase. The 10° diameter simulated scotoma was present in the display exactly as in the induction sessions. Because of the lesser acuity of peripheral vision, Landolt C stimuli are most visible when close to the fovea (close to the border of the scotoma), thus motivating the participants to make eye movements placing the scotoma near the border of the C. Each visual acuity session had 70 trials (~8 minutes). Visual acuity thresholds were calculated as arithmetic means of the last 20 trials.

2.3.3. Visual Search—Participants performed a visual search task in which they were asked to report whether the target (a letter T tilted horizontally) was pointing left or right (whether the larger tip of the letter was pointing left or right) by pressing the corresponding arrow key on the computer keyboard. The target was presented among 11 distractors ('L-like' stimuli). Participants underwent 24 trials per block for 10 blocks. The first two blocks were used as practice and discarded from the analysis.

2.3.4. MNRead—A computerized version of the MNRead task (Mansfield, Ahn, Legge, & Luebker, 1993) was implemented to be performed within the artificial scotoma paradigm. Critical print size, minimum print size and reading speed were then estimated.

2.3.5. Training—During sessions 4 to 13, participants were assigned to one of two training conditions (see Figure 2), Standard perceptual learning (SPL) or Coordinated attentional training (CAT).

In SPL, a Gabor patch was always presented in the center of the screen accompanied by an auditory cue of fixed pitch (500 Hz) and presented unpanned (central), meaning that the training did not require searching for the target but only required identifying whether a low contrast grating was oriented left or right. During CAT, the target could appear anywhere on screen, requiring a search and reorienting of gaze toward the target. The target was accompanied by a visual cue (a circle around the target) that was either bright or dim, meaning that on some trials the location was visually salient but on others it was not. Additionally, during CAT the target was accompanied by an auditory cue indicating its position on the screen: The auditory cue was panned left or right according to the horizontal position of the target (based on interaural time/level differences), and its pitch was higher or lower depending on the target position along the vertical axis. Thus, while SPL training involved a more standard, static perceptual learning paradigm, CAT incorporated shifts of attention toward different cued locations in space. Additional details on the training procedures can be found in Maniglia, Jogin, Visscher and Seitz (2020)

As for the induction procedures, data are here combined across training types, due to the fact that the observed across-subject variability of peripheral looking strategies was larger within than across training conditions. A larger sample size would be required to make robust differentiations between training conditions. However, for those interested in the per-condition effects, the data are displayed as a function of condition in the figures and comparisons between conditions are provided in the Supplementary Material.

2.4. Oculomotor analysis

In this analysis, we computed the amount of ‘target pixel’ (number of pixels belonging to the target) per fixation within each candidate PRL. Figure 3 shows a summary of this analysis. For each task, the visual space outside the scotoma was divided into 8 non-overlapping regions of 6.5 deg diameter distributed radially at 8.5 degrees of eccentricity from the center. To clarify, these regions were not visible in any way to the participant and are simply used in our analysis. For each task, we computed the number of target pixels falling within each region across trials on a frame-by-frame basis. Specifically, for each frame, we computed the target pixels (if any) that fell within one or more of the peripheral regions and we generated proportion of use by dividing the number of target pixels within each region with the overall number of target pixels seen with any of the peripheral regions. Figure provides an example of a frame in which most of target-related pixels are seen through the upper peripheral regions (1-2-8), with few falling within lateral regions (3 and 7) and none seeing through lower regions. On the other hand, Figure 3C shows an example of a frame in which the target elements are mostly seen through regions to the left of the simulated scotoma (7 and 8).

To quantify oculomotor strategies, we created polar plots estimating the amount of task-relevant information for each fixation in each assessment task and compared these within- and across individuals. Specifically, for each task, the visual space outside the scotoma was

divided into 8 regions of 6.5° diameter (candidate PRLs). For each task, we calculated the number of target pixels that fell within each candidate PRL region during each fixation, across trials (see Method). This was converted to a percentage of the total target pixels seen over time at each of the 8 candidate PRLs. Of note, the percentage only takes into account the overall amount of 'target pixels' observed over time; thus the percentage is only relative to the absolute amount of time in which the target was within any of the PRL locations (if, e.g. the target was in the scotoma most of the time, there would be few target pixels observed, and the denominator of the percentage would be small).

3. Results

3.1. PRL location differences across tasks

As a first oculomotor analysis, we compared the probability distribution of the use of each of the 8 candidate PRL locations across tasks (post-test data, Figure 4).

To address that, we performed a two-way ANOVA with factors Task (MNRead, Visual search, Visual acuity) and PRL location (1:8) on logit-transformed percentage data for each PRL in each task. Results showed a main effect of task ($F(2,18) = 12.958$, $p < .001$, $\eta^2 = 0.085$), and a main effect of PRL location ($F(7,63) = 4.431$, $p < 0.001$, $\eta^2 = 0.131$). The Interaction of Task by PRL location was not significant: $F(14, 126) = 1.616$, $p = 0.08$, $\eta^2 = 0.070$). Post hoc tests (Bonferroni-corrected t-tests) showed that the visual acuity task differed significantly from both visual search ($t = 4.517$, $p < 0.001$) and MNread ($t = 4.292$, $p < 0.001$). Post hoc tests (Bonferroni-corrected t-tests) conducted on PRL location showed a significant difference between PRL 3 (right) and PRL 5 (bottom) ($t = 4.347$, $p = 0.001$) and PRL 7 (left) and PRL 5 (bottom), ($t = 4.414$, $p = 0.001$).

3.2. PRL location consistency across tasks

A key question regarding oculomotor behavior following (simulated) central vision loss is whether participants would use the same or different PRL location to perform the different tasks. To address this question, we looked at the most used PRL for each task and each participant.

These data show a split between people using consistent and task specific PRLs, as a total of 8 participants used consistent PRLs across 1 or 2 tasks, while 11 used task-specific PRLs for all tasks. Similar to what was observed in the clinical literature (e.g., Crossland, Culham, Kabanarou, & Rubin, 2005), participants trained in conditions of simulated central vision loss showed a variety of oculomotor behaviors. Of note, some participants exhibited a clearer PRL preference (S6, S12, S17) than others (S8, S13, S14), thus an analysis that only looks at the most used PRL might miss some nuances of peripheral vision use in conditions of simulated central vision loss. Figure 6 shows individual participant data for the three tasks, divided by induction and training condition.

3.3 Effect of induction and training type on peripheral vision use

While the main goal of the present study was to characterize task-dependent differences in peripheral vision use after exposure to simulated scotoma, an additional question is whether

differences in assignment of participants to induction or training type played a role in the observed oculomotor effects. Participants were assigned to one of two induction procedures (assigned PRL or Annulus, see PRL induction in the Method for details) to promote the development of peripheral oculomotor strategies and one of two training types (SPL or CAT, see Method) to test for characteristics of the training task that could affect behavioral outcomes, see Supplementary material.

To test whether induction or training affected oculomotor behaviors during the three tasks here discussed, we conducted a mixed model ANOVA with between factors Induction (Assigned vs Annulus) and Training type (CAT vs SPL) and within factors Task (VA, Search, MNRead) and PRL (1:8). Results confirmed a main effect of Task ($F(2, 18) = 6.72$, $p = 0.007$, $\eta^2 = 0.035$ and PRL ($F(7, 63) = 6.72$, $p < 0.001$, $\eta^2 = 0.117$) from the previous analysis. Additionally, we observed a significant interaction Task × PRL ($F(14, 126) = 1.82$, $p = 0.042$, $\eta^2 = 0.051$) and a significant effect of Training type $F(1, 9) = 18.72$, $p = 0.002$, $\eta^2 = 0.038$). Figure 5 shows average oculomotor behavior divided by training type.

Finally, in the Assigned PRL induction condition, participants were randomly assigned a PRL through which perform their first sessions in conditions of simulated scotoma (see Method). This PRL was either to the left of the scotoma or to the right (see Table 1). To qualitatively assess whether the location of the assigned PRL would bias oculomotor strategies in the three tasks here discussed, we plotted polar plots separated for participants Assigned Left and Assigned Right (collapsing training conditions, Figure 5). An ANOVA conducted on this subgroup of participants showed no significant difference in PRL use distribution between PRL assigned left and PRL assigned right.

Discussion

In this study, we looked at consistency of PRL location across tasks in a group of healthy participants trained with a gaze-contingent, simulated scotoma obstructing the central 10° of their visual field. Results showed an overall bias towards the use of peripheral locations to the left and to the right of the simulated scotoma, with respect to locations below it. Additionally, the pattern of peripheral vision locations use significantly differed between visual search and the other two tasks tested, namely visual acuity and reading.

The first result (the overall left-right bias) is consistent with the idea that PRL selection after central vision loss might be guided toward locations with better sensitivity (‘*performance-driven selection,* Cheung and Legge, 2005). Peripheral vision is characterized by asymmetrical sensitivity distributions (*anisotropies*), where locations along the horizontal meridian have superior sensitivity than other locations, in particular for tasks such as contrast sensitivity (e.g., (Abrams, Nizam, & Carrasco, 2012; Baldwin, Meese, & Baker, 2012) and orientation acuity (Barbot, Xue, & Carrasco, 2021). This is also consistent with clinical evidence from MD patients who spontaneously select PRLs along the horizontal meridian (Crossland et al., 2005).

The second result (significant differences in PRL distribution patterns across tasks) confirms, in the context of simulated central vision loss, a piece of evidence reported in

clinical studies in patients that show the use of different PRLs for different visual tasks (Duret, Issenhuth, & Safran, 1999; Lei & Schuchard, 1997; Safran, Duret, Issenhuth, & Mermoud, 1999; Sullivan, Jovancevic-Misic, Hayhoe, & Sterns, 2008).

Specifically, participants used similar PRLs for the reading speed and the visual search tasks, both of which contained multiple stimuli per trial and required scanning of the whole visual scene. This is different from the oculomotor behavior required during the visual acuity task, in which a single, highly visible stimulus would appear in a random location on screen in each trial. The different nature of these two types of tasks (automatic capture/exogenous attention in the visual acuity task vs patterned eye movements and systematic tracking and in the reading and visual search tasks) might then explain the different peripheral visual field use here observed. These results are consistent with clinical evidence from MD patients showing the use of multiple PRLs depending on characteristics of the tasks (Altpeter, Mackeben, & Trauzettel-Klosinski, 2000; Duret, Issenhuth, & Safran, 1999; Lei & Schuchard, 1997; Safran, Duret, Issenhuth, & Mermoud, 1999; Sullivan, Jovancevic-Misic, Hayhoe, & Sterns, 2008) and with the *function-driven selection* of a PRL proposed by Cheung and Legge (2005). Indeed, If the needs of the task guide task-specific PRL selection, then one would expect that a visual acuity task demands the patient to use a PRL with high resolution, while visual search tasks, in which the goal is discriminating shapes among distractors (e.g., contour integration or segregation), similarly, reading would benefit of a retinal region with reduced crowding (He & Legge, 2017). From an oculomotor standpoint, the visual acuity task would require minimum eye movement (just one or two saccades before landing a PRL on the target), the reading task would require systematic, yet somewhat predictable eye movements (left to right starting from the highest row and then proceeding down), while the search task might require trial-by-trial strategies depending on the location of the elements on screen. Moreover, there is evidence of perceptual heterogeneity of stimulus and task features across the visual field, so that different portions of the visual field might be more or less ideally suited for the needs of each task (Afraz, Pashkam, & Cavanagh, 2010). Finally, while visual acuity involves mostly local processes, reading seems to involve both local and global processing (Just & Carpenter, 1980; Rayner, Raney, & Sereno, 1996).

To summarize, the needs of the tasks (low level orientation discrimination for visual acuity, explorative eye movements and contour segregation for visual search, and crowding and systematic eye movements for reading) might dictate which peripheral location should preferentially be used. Of note, Lei and Schuchard (1997) reported a consistent shift in the PRL of MD patients following changes in the stimulus luminance. Specifically, they observed that patients tended to use PRLs closer to the fovea or scotoma and with better fixation stability for brighter stimuli, shifting to PRLs further away from the scotoma for low luminance stimuli. In the present study all the visual stimuli were of high luminance against a gray background, thus stimulus luminance could represent an additional parameter to consider in further exploration of task-dependent PRL use.

Simulation of central vision loss in healthy participants has been successfully used in recent years to model visual pathologies such as macular degeneration (Barraza-Bernal, Ivanov, et al., 2017; Barraza-Bernal, Rifai, & Wahl, 2017; Kwon, Nandy, & Tjan, 2013; Liu &

Kwon, 2016; Maniglia, Jogin, Seitz, & Maniglia, 2020; Maniglia, Visscher, & Seitz, 2020; Walsh & Liu, 2014), and oculomotor analysis shows that a PRL can be induced with this paradigm. Despite differences in the characteristics of the scotoma (visible, opaque, hardedged in simulated condition vs irregular shapes and various degrees of awareness of it in MD patients) and time course of PRL development (months in MD patients, hours in healthy participants), there is optimism in the use of the simulated scotoma framework to study compensatory oculomotor mechanisms and test possible rehabilitative interventions.

The large majority of the participants (12 out of 19) used different PRLs for different tasks, with only 4 out of 19 using a single PRL across all tasks. Overall, we observed a variety of oculomotor behaviors, with some participants adopting consistent looking strategies across tasks whereas others shifted peripheral looking strategies across tasks or time. Heterogeneity of oculomotor behavior in healthy participants trained with artificial scotomas seems to mirror what observed in patients. In general, our understanding of the mechanisms of peripheral vision are at least partially limited by the large volume of data that would be needed in order to comprehensively characterize peripheral visual functions over multiple regions of space. Similarly, clinical assessments of visual field integrity (visual field maps, VFMs) are usually limited to light sensitivity (Dreyer, 1993; Johnson, Wall, & Thompson, 2011) while tests to estimate other visual functions such as color sensitivity, reading speed, crowding etc, are rarely used or are measured in a single location, either in central vision or at a single peripheral location (Dorr et al., 2015; Hou et al., 2010). Indeed, new methods aiming at this multidimensional characterization of peripheral visual functions are being developed (Xu, Lesmes, Yu, & Lu, 2019, 2020), but are still far from being commonly used.

In this study, participants underwent one of two PRL induction procedures (to promote development of oculomotor strategies) and one of two training types (SPL or CAT). While the main goal of this paper was to characterize task-dependent differences in oculomotor behavior in conditions of simulated central vision loss, we conducted additional analysis to explore the effect of these two manipulations. Results showed that the overall use of peripheral vision differed between SPL and CAT, which may be a result of the different needs of the two tasks: Indeed, while in CAT targets could appear anywhere on screen, prompted by a visual cue, in SPL the target was always presented centrally. Additionally, we looked at the subgroup of participants to which a PRL to the left or to the right of the scotoma was assigned during induction. Statistical analysis on this subgroup of participants did not show a significant effect of the assigned PRL location on PRL use during the three assessment tasks. However, it is important to consider the small number of participants for each combination of conditions, which adds to the already large inter-individual differences in eye movement strategies.

More data is needed to understand how perceptual and oculomotor characteristics of training may affect the development of eye movement strategies in conditions of simulated central vision loss.

This study represents one of the first examinations of the extent to which peripheral looking strategies are consistent or not within cases of simulated central vision loss across tasks.

Individual differences in peripheral looking strategies observed in simulated central vision loss may model those developed in pathological vision loss.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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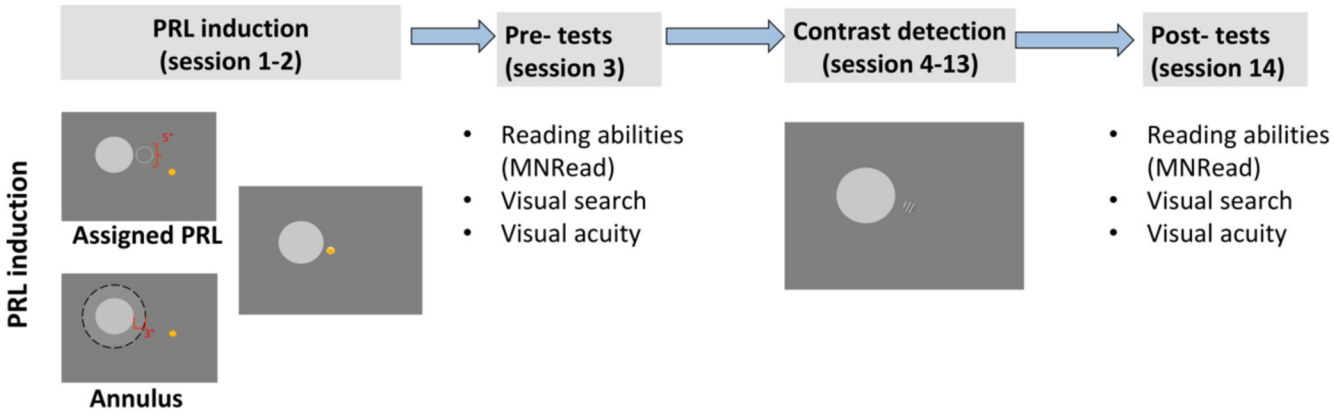

Figure 1: Layout of the study:
each participant underwent 14 sessions, structured as follows: two sessions of PRL induction, one session of pre-tests, 10 training sessions and one session of post-tests.

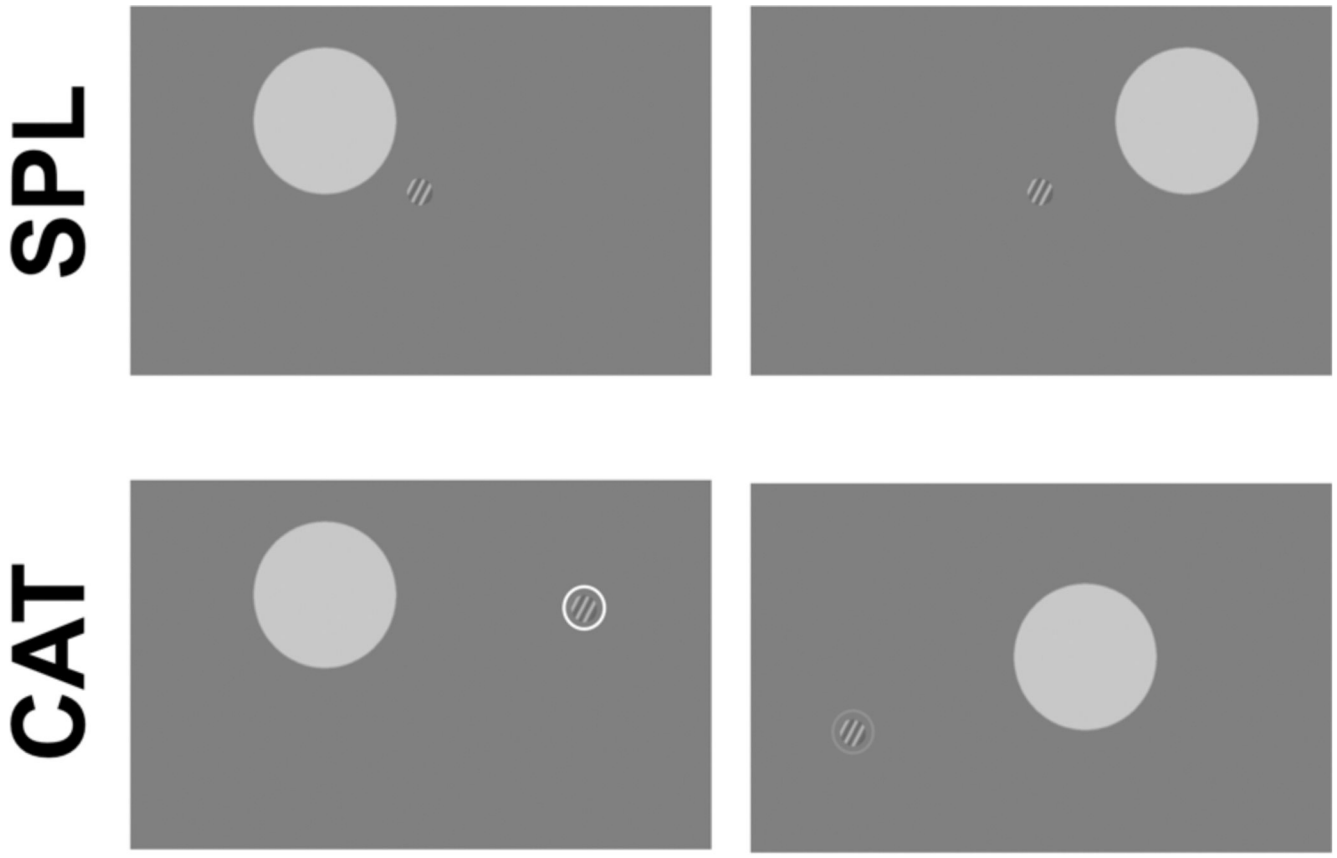

Figure 2: Training types:
examples of two trials for each type of training. During SPL (*top*), the target always appeared in the center of the screen. During CAT (*bottom*), the target could appear anywhere on the screen, accompanied by an auditory cue (whose pitch and inter-aural time difference would indicate its position on the screen), and a visual cue (bright circle, left, or dim circle, right). During both training types, a gaze contingent simulated scotoma of 10° diameter would obstruct participant's central vision in real time (exemplified here by the different position of the scotoma on the screen).

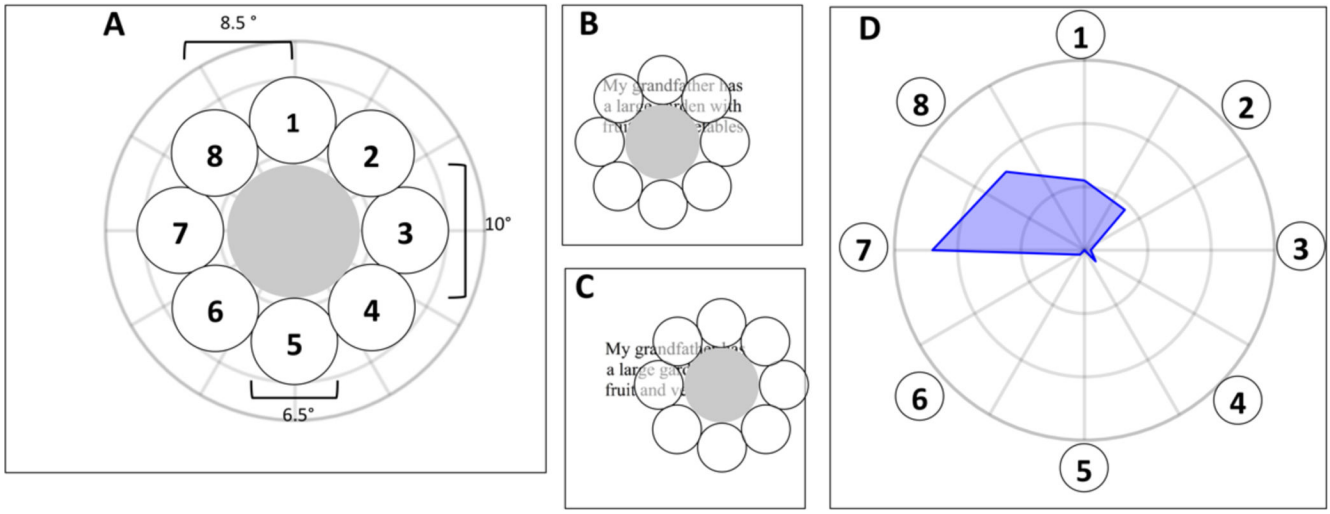

Figure 3:

A: visual space divided into 8 radially distributed candidate PRL locations outside the simulated scotoma **B**: Example of the analysis for a frame during the MNRead task, in which mostly upper PRLs are used to see the stimuli. In this case, the amount of target information (number of 'target pixels') within each region would be skewed towards PRL 1, 2 and 8, and to lesser extent to 3 and 7. No target pixels fall within the remaining PRLs. **C**: same as B but an example where mostly left PRLs have target information. **D**: proportional distribution of target pixels (percentage of total target pixels) within each of the 8 regions for a full session of MNRead. In this example the analysis shows that for this participant most of the target elements (i.e., the words in the MNRead) were observed through regions 3 and 7, corresponding to areas to the left and to the right of the scotoma.

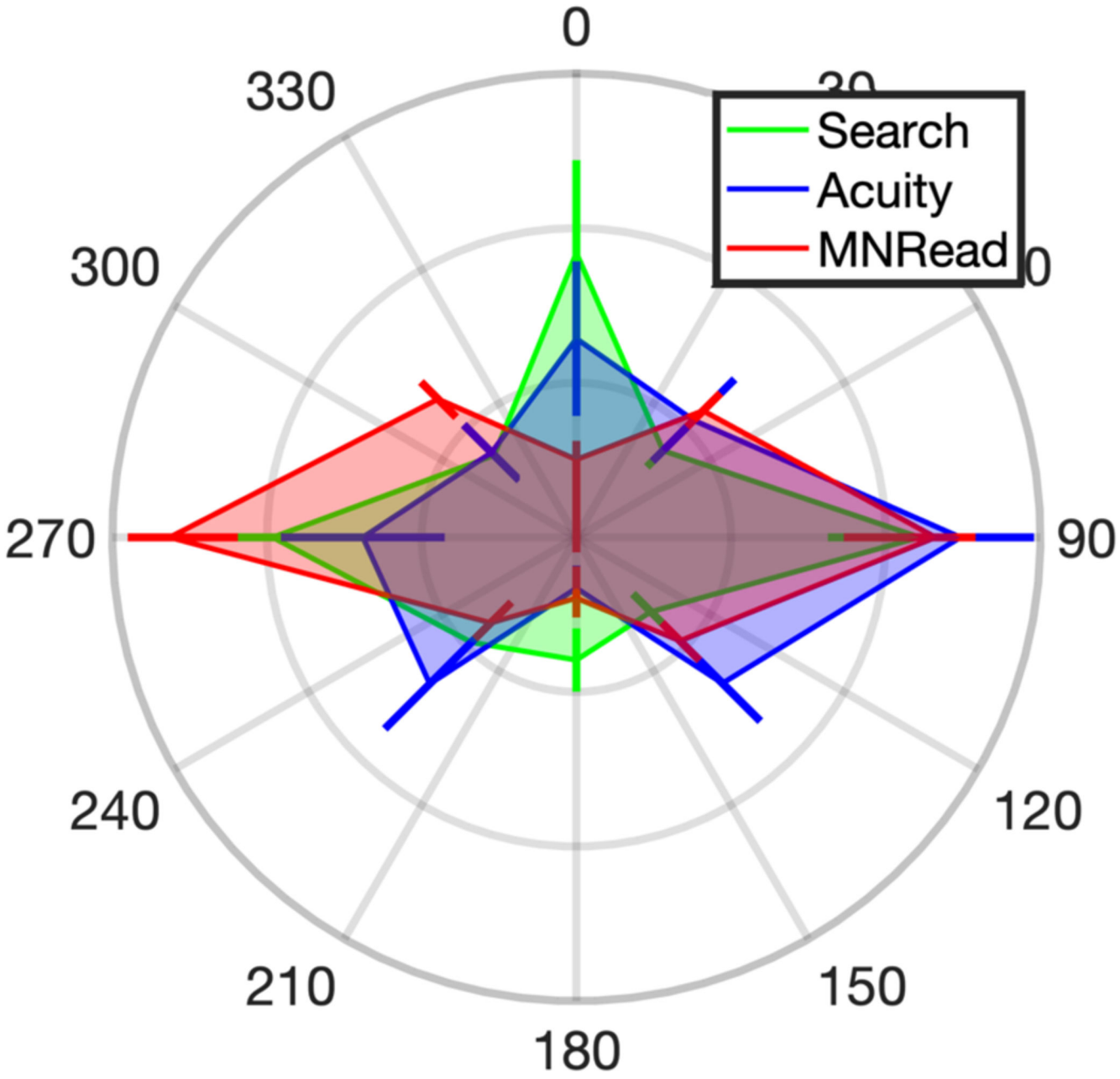

Figure 4:
Polar graph representing the average PRL location (radial axis representing the % of use of each PRL per session) during MNread (red), visual search (green) and visual acuity (blue) after contrast detection training in conditions of simulated scotoma. Error bars represent SEM.

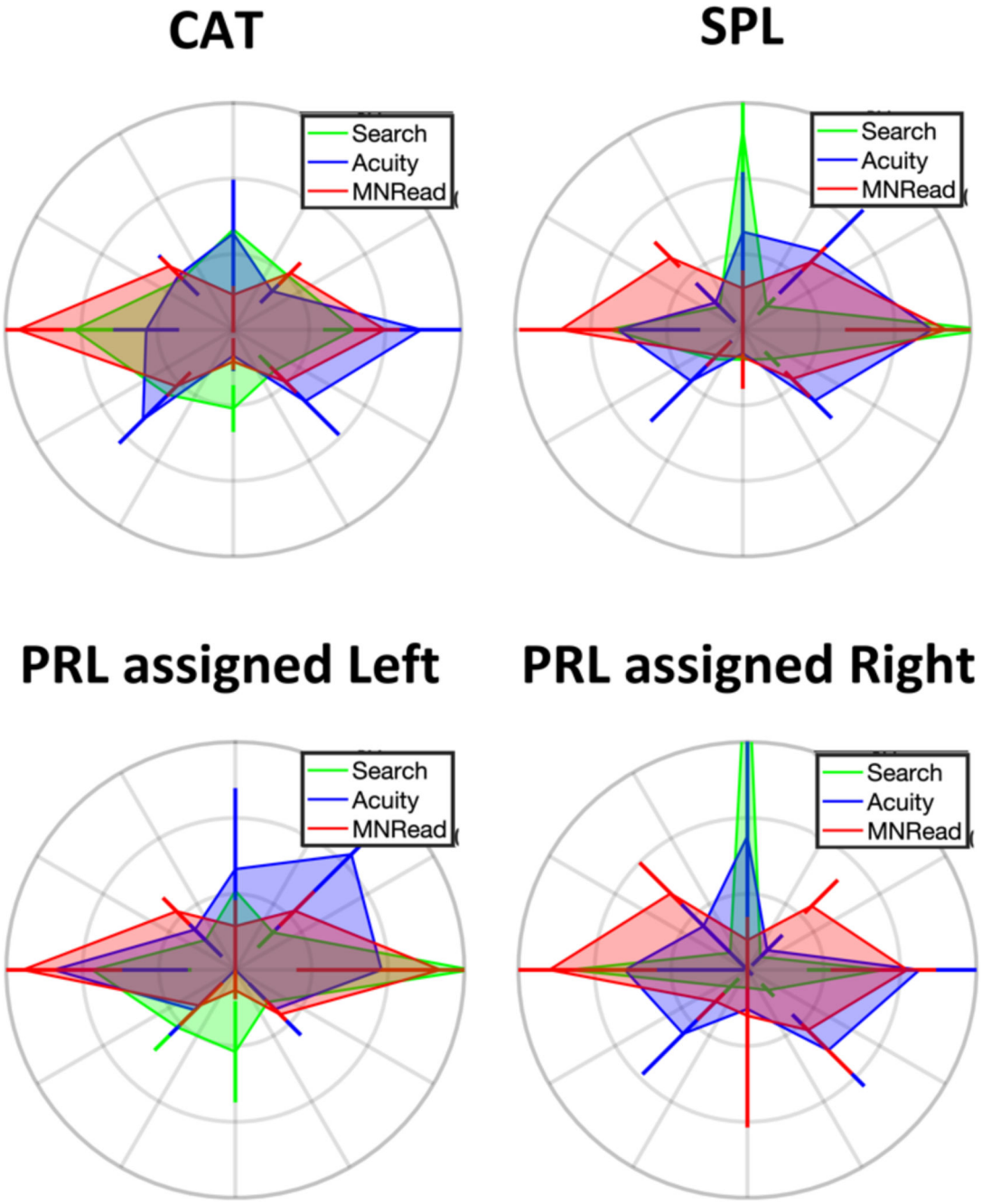

Figure 5:

Above: Polar graph representing the average PRL location during MNread (red), visual search (green) and visual acuity (blue) after CAT and SPL training (left and right, respectively). Below: average PRL location during MNread (red), visual search (green) and visual acuity (blue) for participants that underwent PRL induction with Assigned PRL to the left and to the right. Error bars represent SEM.

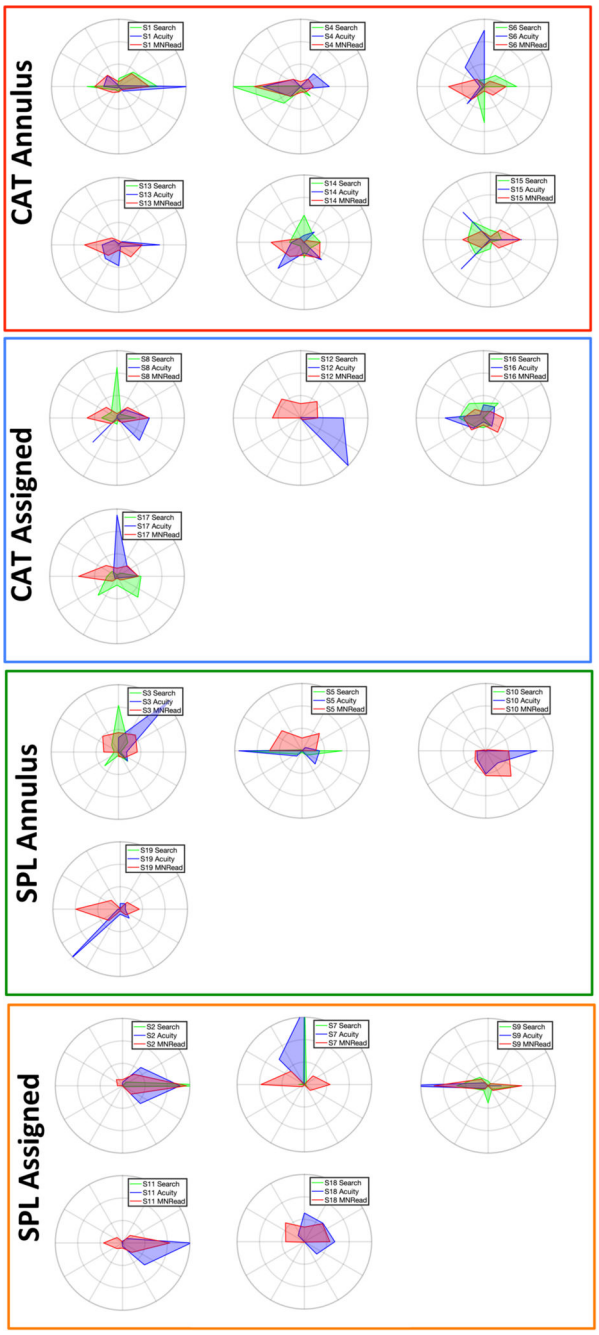

Figure 6:
Individual participant data for the PRL use across tasks, divided by induction (assigned vs annulus) and training (CAT vs SPL) condition

Table 1:

Breakdown of PRL location assignment and training type for participants who underwent the Assigned PRL induction procedure.

Participant	Assigned PRL	Training type
S2	Left	SPL
S7	Left	SPL
S8	Left	CAT
S9	Right	SPL
S11	Left	SPL
S12	Right	CAT
S16	Right	CAT
S17	Left	CAT
S18	Right	SPL