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Peripheral oculomotor training in individuals with healthy visual systems: Effects of training and training transfer

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A R T I C L E I N F O

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A B S T R A C T

Individuals with pathological or simulated central visual field loss can be trained to use a preferred retinal locus (PRL) as a substitute for their non-functioning fovea. The functional benefits of a stable PRL are well documented, but little is known about oculomotor adaptations during PRL acquisition or transfer of training to another location in response to real or simulated disease progression. In this study, eight normally-sighted observers were trained to use a pseudo-PRL (pPRL) at one of two locations by guiding an eccentrically placed, gaze-contingent ring over a fixation target. The pPRL location was 6.4 degrees in either inferior or right visual field, balanced across observers. Training was completed in two sessions of 200 hundred trials separated by a week. Between sessions, the pPRL position was switched. Task performance was quantified both in terms of gaze stability around the fixation target and gaze accuracy in terms of distance between the target and ring centers. The latter was used to provide feedback by covarying the diameter of the ring to make the task easier or harder on the basis of subject performance. Accuracy and stability significantly increased with training and was comparable at each trained location. Performance gains were retained over a week and transferred from the first to the second pPRL location. Thus, pPRL training with feedback can provide sustained, generalizable improvements in oculomotor control following simulated foveal vision loss. These results suggest that low vision rehabilitation specialists may prioritize PRL training locations based on sensory function alone, since oculomotor gains are relatively uniform; and that training early in the disease process may benefit later adaptations should eye disease progress.

1. Introduction

Individuals with retinal diseases such as age-related macular degeneration (AMD) that damage or destroy the fovea may develop one or more preferred retinal loci (PRL) as a compensatory adaptation to loss of vision in the center of the visual field (Fletcher and Schuchard, 1997; Von and Mackensen, 1962; Whittaker et al., 1988; White and Bedell, 1990; Whittaker et al., 1991). Over the course of weeks to months, either a single general-purpose PRL (Fletcher and Schuchard, 1997; Von and Mackensen, 1962; Whittaker et al., 1988) or a series of often task-specific PRLs (Timberlake et al., 1986) may be adopted. However, in spite of the substantial literature documenting the *existence* of PRLs, relatively little is known about the processes by which they are formed and whether formation at certain retinal locations may lead to superior performance on visual tasks relative to others.

It has been demonstrated that the formation of a PRL is associated with improved functional vision outcomes in tasks such as reading (Crossland et al., 2004; Seiple et al., 2005; Palmer et al., 2010). Low-vision rehabilitation specialists therefore may train a PRL in patients with pathological central vision loss (Schuchard, 2005; Watson et al., 2006). However, few studies have specifically examined changes in oculomotor control during the *acquisition* of a PRL (Crossland et al., 2004). Understanding these processes is important, as many visual tasks require precise eye movement control, and its loss may impair visual function independently of retinal pathologies that directly affect sensory performance. This idea is supported by converging lines of evidence indicating both that fovea loss is associated with changes in oculomotor control (Bullimore and Bailey, 1995; Crossland et al., 2004; Schuchard, 2005) and that even at supposedly spared retinal locations at the same eccentricities, individuals with central field loss perform many tasks less well than individuals with healthy vision (McMahon et al., 1991; Mcmahon et al., 1993Mcmahon et al., 1993; Timberlake et al., 1986).

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One of the reasons for the relatively limited research in this area may be that there are substantial technical and methodological challenges associated with collecting eye movement data from patients with retinal disease. Patient populations express highly variable symptom profiles, making it difficult to obtain homogeneous samples of subjects for experimental purposes (Bowers and Reid, 1997). Fixational instability that accompanies fovea loss makes calibration of eye tracking systems on patients difficult. One method used to overcome these problems is to simulate central scotomas in individuals with healthy vision using gaze contingent stimuli on computer displays (e.g. Aguilar and Castet, 2011; McIlreavy et al., 2012). These simulations have numerous limitations, but if carefully controlled, can provide good approximations of the perceptual and behavioral consequences of visual impairments (Bowers and Reid, 1997). Simulations also facilitate the use of statistically powerful within-subjects/cross-over experimental designs, which would be difficult or impossible to implement among patients.

A small but growing literature exists suggesting that over the course of several hours of explicit training using simulated scotomas, individuals with healthy retinas can also form a "PRL-Like" region (Kwon et al., 2013; Varsori et al., 2004; Walsh and Liu, 2014). We term this a "pseudo-PRL" (pPRL) because it is functionally similar to a true PRL but is not a product of a disease processes. The possibility of training pPRLs means that it may be possible to study oculomotor control during PRL development without invoking the difficulties associated with tracking the eye movements of patients with central scotomas. We therefore used a pPRL induction paradigm to ask the following questions:

- Does pPRL training reduce fixational stability and the magnitude of oculomotor deviations or errors around a target? Such changes are thought to be an important part of the process of adaptation to retinal disease (Crossland et al., 2004), and are considered an important objective in rehabilitation programs as well (Mandelcorn et al., 2013). These findings further point to the important role that both implicit (natural process of response to disease progression in unmanaged retinal disease) and explicit (direction through rehabilitation training) feedback plays in the stabilization of a PRL. Explicit feedback in particular has been shown to improve treatment outcomes during visual rehabilitation training in response closs (Contestabile et al., 2002; Hall and Ciuffreda, 2001Hall and Ciuffreda, 2001; Pusswald et al., 2013; Vingolo et al., 2007). To our knowledge, however, there is little available data on changes to oculomotor control as *a function of* the implicit time-course of training or practice at a PRL or pPRL site (though see Kwon et al., 2013; Varsori et al., 2004; Walsh and Liu, 2014 for some discussion of this issue).
- Are oculomotor control changes associated with pPRL development affected by meridional performance differences across the retina? Although it is generally understood that functional vision and oculomotor control performance fall as a function of increasing retinal *eccentricity*, there is debate regarding the merits of selecting a PRL at specific retinal *orientations* relative to the fovea. There are well-documented meridional asymmetries in visual function such as acuity and contrast sensitivity (Skrandies, 1987), attentional resolution (Rezec and Dobkins, 2004) and the volitional control of "sustained" attention (Alpeter et al., 2000; MacKeben, 1999MacKeben, 1999), chromatic sensitivity (Levine and McAnany, 2005), motion sensitivity (Edwards and Badcock, 1993; Levine and McAnany, 2005), and crowding (He et al., 1996).
- Is pPRL training retained across time and transferred across locations? Many retinal diseases progress over time and therefore a trained PRL may eventually be claimed by an advancing lesion (Nilsson et al., 1998). We therefore examine whether effects of pPRL training at one location are "carried over" to subsequent training at a different location.

It is important to note that while these questions and the methods we have chosen to address them are strongly informed by current research on pPRL induction, our approach differs in one important respect. Specifically, because we wished to test whether training transfers between locations, subjects were not permitted to*select the pPRL site for themselves*. This is undoubtedly a key feature of the development of true PRL, and thus an important component of a realistic simulation of the same process with pPRL. However, it would be difficult or impossible to have subjects spontaneously select pPRL locations that were equally eccentric but in different locations, or to maintain a constant distance between trained locations.

2. Materials & methods

Eye movement data for this project were collected using an SR Research Eyelink 1000 infrared eye tracking system. Stimuli were presented on a 68.58 cm diagonal width ASUS VG278He monitor running at a 144 Hz refresh rate. Subjects were seated at a distance of 55 cm from the display, which therefore subtended a 54° horizontal visual angle. Subjects' heads were stabilized during the experiment using an Eyelink-supplied chin and forehead rest. Stimuli were generated, displayed, and modified in real time on the basis of input from the Eyelink through the use of the MATLAB Psychtoolbox (Brainard, 1997) and Eyelink Toolbox (Cornelissen et al., 2002). Data were sampled at a rate set to match the refresh rate of the monitor. Subjects' gaze profile was calibrated to the display using the standard nine-point calibration protocol provided with the Eyelink before each experimental session began.

Eight participants (six women, two men) with normal or corrected-to-normal vision were recruited from the authors' laboratory and from the undergraduate population at Northeastern University. Undergraduates received course credit towards the completion of their introductory psychology course in exchange for their participation. All were naive to the purposes of the study at intake and indicated their willingness to participate by signing an informed consent document associated with a protocol approved by the University Ethics Board. The Northeastern University Ethics Board evaluated the protocol and confirmed that this research adhered to the tenets of the Declaration of Helsinki.

Participants completed a total of 400 training trials, split into two training sessions of 200 trials each. Sessions were separated by a period of roughly one week (mean 8.6 days, sd 3.2 days). Within a session, each subject completed four blocks of 50 trials. Between blocks, they were asked to rest for as long as they felt they needed. All were then re-calibrated using the same nine-point calibration procedure before continuing the experiment.

Trials lasted for fifteen seconds. During a trial, subjects were asked to center a gaze contingent ring over a motionless fixation target and to maintain that position for as long as they were able (see Fig. 1 for a schematic representation of the task). The fixation target was a full-contrast red (RGB: [255,0,0]) circle with a diameter of 24 pixels. The line forming the gaze contingent ring was three pixels wide and drawn as a full contrast green (RGB: [0,255,0]). Trials fell into one of two orientation conditions: "east" or "south". In the east, the ring was drawn 6.4° (128 pixels) to the right, and in the south 6.4° below, the foveated point of regard. Each session contained trials associated with one condition. At the beginning of the second training session, subjects switched conditions. The order in which they were completed was counterbalanced between subjects.