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Eye Movements in Visual Impairment

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Abstract

This *Special Issue* describes the impact of visual impairment on visuomotor function. It includes contributions that examine gaze control in conditions associated with abnormal visual development such as amblyopia, dyslexia and neurofibromatosis as well as disorders associated with field loss later in life, such as macular degeneration and stroke. Specifically, the papers address both gaze holding (fixation), and gaze-following behavior (single saccades, sequences of saccades and smooth-pursuit) that characterize active vision in daily life and evaluate the influence of both pathological and simulated field loss. Several papers address the challenges to reading and visual search; describing how the patterns of eye movements in these real-world tasks adapt to visual impairment and highlighting how they could serve as diagnostic markers of visuomotor function.

Keywords

amblyopia; dyslexia; neurofibromatosis; macular degeneration; hemianopia; central field loss; simulated vision loss; reading; visual search; fixation; saccades; smooth pursuit

Eye movements are made by a very broad range of species, particularly those with a retinal region of higher spatial sensitivity. Our eye movements support a wide range of sensory and motor visual behaviors. In some instances, we use saccades to quickly redirect the line of sight to a new object of interest, whilst in others eye movements such as fixation and smooth pursuit are used to stabilize the world on the retina to support detailed spatial analysis or prevent the unwanted experience of motion blur (Leigh & Zee, 1999).

When sampling a visual scene, humans, and many other species with mobile eyes, adopt a saccade and fixate strategy. During periods of fixation, the quality of the eyes optical

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system, the packing arrangement of retinal cones and the degree of receptor pooling at the output layers (retinal ganglion cells) largely determine the limits of spatial detail that can be resolved (Campbell & Green, 1965; Curcio et al., 1987; Curcio & Allen, 1990). More recently, evidence has emerged that small fixational eye movements, present during attempted fixation, may also play an important functional role in enhancing visual quality (Ratnam et al., 2017; Anderson et al., 2020). When the eye relocates to new objects of interest with a saccade, the image is rapidly displaced across the retina. For saccades, different constraints come into play. Here, the temporal response of the receptors must match the change in the light energy distribution as the image passes across the receptive field. Retinal receptors typically have a response profile that is measured over tens of milliseconds (Krauskopf & Mollon, 1971), limiting the rate of luminance fluctuation that can be represented with reasonable fidelity. Because the human visual system is band-pass in both the spatial-frequency and temporal-frequency domain, there will be a limit to how fast a target of fixed spatial frequency can move across the retina before contrast loss (or motion blur) is experienced (Kelly, 1985, Burr & Ross, 1992). For the high-resolution fovea with small receptive fields, best suited to analyzing higher spatial-frequency information, contrast loss will occur even at relatively low image speeds. The visual system has two potential solutions to this problem. First, when a saccade is made to a new location and a loss of image contrast is unavoidable, visual input is suppressed just before and during the eye movement, effectively removing it from visual awareness (Wurtz, 2008). Second, if the object itself is moving an attempt can be made to follow it, limiting the degree of slip on the retina. Visual systems have evolved highly effective gaze-holding mechanisms (e.g. the vestibular ocular reflex and optokinetic response) alongside smooth pursuit eye movements. Importantly, gaze tracking and holding movements that are driven by visual input are slow and rely on good foveal function.

For these reasons, conditions that impair vision at and around the fovea will impact acuity and sensitivity for static and dynamic targets and our ability to maintain perceptual stability with eye movements. Even when foveal function is preserved, visual field defects such as hemianopia can obscure information of interest and the normal pattern of eye movements that are executed in information-seeking tasks such as reading and visual search become highly abnormal.

Several articles in this *Special Issue* address eye-movement patterns that occur in the presence of central field loss (CFL), as this condition serves as a good model to understand how eye movements adapt to the loss of the fovea as an oculomotor reference. One adaptation which occurs is the development of an alternate locus for fixation (or preferred retinal locus, PRL) that is outside the scotoma and used for visual inspection, and which acts as a new reference for eye movements. Since CFL results in the loss of high-resolution information, everyday tasks which require this information will be impacted. Thus, tasks such as reading and visual search, which combine eye movements and information gathering (active vision) become especially challenging. In particular, reading is a task that requires high-resolution vision to perceive each word, and that engenders a stereotypical sequence of fixations to acquire the information at the gaze location, followed by subsequent saccades to target later words. Disruptions to the pattern of fixations and forward saccades can therefore be used to evaluate the functional consequence of visual impairment in CFL, but also in conditions such as hemianopia (loss of either the left or right half of the visual field) and neurodevelopment disorders associated with reading impairment (such as dyslexia or neurofibromatosis).

In the following sections, we preview papers that address eye movements in visual impairment: during fixation, single saccades, and the sequences of saccades that characterize active vision in daily life

Fixation

In normal viewing, fixation (maintaining a steady gaze on the target of interest) allows us to sample information at a particular location in space. Despite our attempts to keep the eye stationary, fixational eye movements, such as microsaccades, drift and tremor, are present. Small amounts of drift may actually improve sampling of high spatial frequency information (Rucci & Victor, 2015), but studies have shown that the stability of fixation is outside these norms in conditions such as amblyopia and strabismus (Schor & Hallmark, 1978; Chung et al. 2015) and in central field loss (Tarita-Nistor et al., 2009). Amblyopia, particularly with strabismus, is associated with poor fixation stability (Subramanian et al., 2013). More recently, it has been suggested that poorer fixation stability may be a natural adaptation to central acuity loss, particularly when the instability arises from an increase in the amplitude of microsaccades (Mostofi et al., 2020). Saccadic latencies to a target presented in the periphery are also delayed in amblyopia, compared to visually healthy controls (Ciuffreda et al., 1978; McKee et al., 2016; Gambacorta et al., 2018). Fixation instability of the amblyopic eye has previously been proposed as a potential reason for this longer saccadic latency (Verghese et.al., 2019), but a study in this *Special Issue* by Chow et al. (2022) suggests that attentional disengagement from a fixational marker may also play a role. It appears that presenting the fixation target to one eye, and the saccade target to the other, significantly reduces saccadic latency of the amblyopic eye, making it comparable to the fellow eye, and suggesting that it is disengagement from fixation that may be abnormal in the amblyopic eye.

In amblyopia, the retina is intact and the impact of ocular misalignment or uncorrected blur in one eye is reflected in impaired connectivity at the level of primary visual cortex. The question of how individuals adapt to a loss that occurs at the level of the retina and includes the fovea, is examined in a study by Vice et al. (2023). This study simulated central field loss using a gaze-contingent scotoma in normally sighted observers. By using the active target-following protocol of Liu and Kwon (2016), where a target is displaced as soon as the observer responds to its identity, the study included a more natural eye movement sequence than static fixation training. The stability of the retinal locus used to view the target improved considerably post-training, demonstrating that fixation can be improved effectively with an active training protocol. This suggests it may be possible to reduce fixational instability in central field loss and perhaps amblyopia via active training.

The development of a consistent retinal locus as a reference for eye movements

To expedite the adoption of a consistent locus for fixation and for eye movements, Vice et al., (2023) assigned a specific retinal locus outside the scotoma to individual observers. Remarkably, after 12 training sessions with a simulated central scotoma, observers not only demonstrated stable fixation with the trained locus, but also used it consistently as a reference for eye movements. Maniglia et al., (2023) went a step further and asked if the locus developed during training with an artificial scotoma, also generalized to other tasks. Interestingly, they found that after training observers were quite variable in whether they used a consistent viewing strategy across three tasks: an acuity task, a reading task and a visual search task. Some observers used reasonably consistent strategies, whereas others used different strategies depending on the task. This relates to reports that some individuals with CFL use a range of preferred retinal loci, depending on light level and the task (Lei & Schuchard, 1997; Duret et al., 1999). Observers in the Maniglia et al., (2023) study were split into smaller groups that were related to different training protocols and different spatial regions for PRL training. Thus, it is not clear whether these factors account for some of the variability in their results, or whether they represent true heterogeneity of viewing strategy in CFL.

The question of how consistently the PRL is used to follow a moving target was examined by Shanidze et al. (2022). Previously, this group showed that pursuit eye movements have lower gain in individuals with central field loss due to macular disease (Shanidze et al., 2016, 2017). Here they examined saccades during pursuit, to determine whether individuals with CFL use catch-up saccades to improve tracking accuracy of a moving target. They showed that saccades were more numerous during smooth pursuit in CFL compared with controls and that they were broadly distributed in direction with respect to the moving target. Controls, in contrast, produced saccades that were mostly in the direction of the target, i.e., true catch-up saccades. Furthermore, for those with CFL, the distributions of saccade amplitude and direction during fixation and those during smooth pursuit were correlated. Thus, the instability of the eye due to eccentric fixation appears to affect both fixation and smooth pursuit in CFL.

Vrijling et al. (2023) took advantage of the natural tendency to track moving targets to develop a visual field assessment tool, based on continuous eye tracking. Participants were asked to track a moving target that either moved smoothly (pursuit mode), or moved smoothly with sudden displacements at random times (saccadic pursuit), causing the target to traverse peripheral retina. They measured the similarity of observers' eye movements to target motion, with the rationale that a reduction in target visibility as the stimulus traversed the retina would lead to a corresponding decrease in tracking performance. To quantify the role of target visibility, they measured tracking performance in both younger and older participants as a function of contrast. Their results show that in the saccadic pursuit mode, where a target is tracked across the periphery, the tracking metric is highly correlated with peripheral contrast thresholds measured with static perimetry, providing an essential first step to demonstrate the feasibility of continuous eye tracking perimetry.

Eye movements in scene viewing and visual search

Two studies in the *Special Issue* examine how eye movements in CFL are used to gather information during scene viewing (Nuthmann et al., 2022) and visual search (Vullings et al., 2022). The tasks in these two studies approximate eye movements under more naturalistic viewing conditions as participants were looking at images of everyday scenes. During such tasks, there is a bias to keeping eye movements toward the center of the image (Tatler, 2007). However, this tendency is much more pronounced in individuals with CFL and they are less likely to explore image regions farther from the center (Nuthmann et al., 2022) compared to age-matched controls. Nevertheless, eye movements in CFL continued to be drawn to salient image regions to a similar extent as in controls.

Vullings et al. (2022) also used natural images to study information gathering with eye movements in CFL. They superimposed a variable number of Gaussian blobs on the images and asked observers to report the number of blobs. To understand whether eye movements tried to uncover regions hidden by the scotoma to find the targets, the authors first measured the binocular scotoma in individuals with CFL (Vullings & Verghese, 2021), and then eye movements with respect to the scotoma. They found that individuals with CFL tended to make more saccades toward their scotoma, and that these saccades were significantly smaller in magnitude, whereas saccades in non-scotoma directions were similar in amplitude to saccades of age-matched controls. This explains why other studies have found saccade amplitude, when averaged across direction, to be smaller in CFL (van der Stigchel et al., 2013; Nuthmann et al., 2022). Furthermore, Vullings et al. (2022) found that after making a saccade toward the scotoma, observers with CFL often made a backward saccade to inspect the area of the image that had just been uncovered by the preceding eye movement. These backward saccades seem to be an adaptive strategy in CFL to recover information that was previously hidden, and have also been reported during reading in CFL (Bullimore & Bailey, 1995). In the reading literature, backward saccades are used in general as markers of reading difficulty due to vision-related or neurodevelopment-related reading challenges (see also Beh et al., 2023).

Reading

Several articles in this *Special Issue* investigate challenges to reading with visual field loss (CFL and hemianopia) as well as in neurodevelopmental disorders such as neurofibromatosis and developmental dyslexia. In CFL, reading is challenging because acuity is compromised and because the scotoma obscures part of the text. One way to overcome this is to present text at the preferred retinal locus (PRL), one word at a time, in serial order. However, if the word is centered on the PRL, which is often at the edge of the scotoma, it could be obscured by the scotoma. To overcome this challenge, Snell et al., (2023) experimented with multiple instances of the same word, presented around the scotoma, at a scale that was visible in the periphery. This method maintained the serial nature of the presentation, but did not require the observer to fixate accurately with the PRL. Furthermore, presenting at multiple locations made the target word less sensitive to the exact position of the PRL. They found that this method improved reading speed considerably for individuals with CFL.

Beh et al. (2023) examined a simulation of field loss to characterize the challenge of reading with hemianopia (e.g. Zihl, 1996). Reading is likely impacted in hemianopia because field loss reduces the visible window around fixation, (perceptual span, McConkie and Rayner, 1975), affecting both reading speed and the placement of the next saccade. Beh et al. (2023) simulated a gaze-contingent field defect that blurred one half of the display and measured how the degree of blur affected reading speed, as well as the patterns of forward and regressive saccades. Their data capture many of the essential features of reading difficulties and saccade characteristics that impair reading in patients with hemianopia. Furthermore, varying the blur provides a metric to simulate the depth of the hemianopia, providing a tool to quantify the effect of therapy to ameliorate hemianopia.

Vernet et al. (2023) used eye movements to compare reading behavior in two neurodevelopmental populations with known incidence of reading difficulty: developmental dyslexia and neurofibromatosis (NF). Specifically, they examined one component of skilled reading: the ability to make a saccade to the most efficient position within a word. Landing positions were compared between the two clinical groups and with age-matched controls. The results showed that the eye movements of the poor readers in the NF group were similar to those with dyslexia, with more variable landing positions within the word, less sensitivity to the gaps between words, and a different effect of hemifield. The authors relate these patterns to the automization of scanning during reading. Detailed analysis of clusters of participants (e.g., NF children with and without reading deficits) suggests underlying eye movement behaviors which are associated with reading efficiency. This indicates that abnormal visuomotor function may be a common factor in both dyslexia and NF.

Taken together, the papers in this *Special Issue* demonstrate that eye movements are a versatile tool for studying visual impairment. Understanding how real and simulated visual impairment changes eye movement behavior can provide new insights, in both simplified clinical tasks and in everyday situations such as reading.

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