REVIEW

Eye Tracking to Assess the Functional Consequences of Vision Impairment: A Systematic Review

Ward Nieboer, MSc,[1,2*] Andrea Ghiani, MSc,[1] Ralph de Vries, MSc,[3] Eli Brenner, PhD,[1] and David L. Mann, PhD[1]

BACKGROUND: Eye tracking is a promising method for objectively assessing functional visual capabilities, but its suitability remains unclear when assessing the vision of people with vision impairment. In particular, accurate eye tracking typically relies on a stable and reliable image of the pupil and cornea, which may be compromised by abnormalities associated with vision impairment (e.g., nystagmus, aniridia).

OBJECTIVES: This study aimed to establish the degree to which video-based eye tracking can be used to assess visual function in the presence of vision impairment.

DATA SOURCES: A systematic review was conducted using PubMed, EMBASE, and Web of Science databases, encompassing literature from inception to July 2022.

STUDY ELIGIBILITY CRITERIA, PARTICIPANTS, AND INTERVENTIONS: Studies included in the review used video-based eye tracking, included individuals with vision impairment, and used screen-based tasks unrelated to practiced skills such as reading or driving.

STUDY APPRAISAL AND SYNTHESIS METHODS: The included studies were assessed for quality using the Strengthening the Reporting of Observational Studies in Epidemiology assessment tool. Data extraction and synthesis were performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines.

RESULTS: Our analysis revealed that five common tests of visual function were used: (i) fixation stability, (ii) smooth pursuit, (iii) saccades, (iv) free viewing, and (v) visual search. The studies reported considerable success when testing individuals with vision impairment, yielding usable data from 96.5% of participants.

LIMITATIONS: There was an overrepresentation of conditions affecting the optic nerve or macula and an underrepresentation of conditions affecting the anterior segment or peripheral retina.

CONCLUSIONS AND IMPLICATIONS OF KEY FINDINGS: The results offer promise for the use of eye tracking to assess the visual function of a considerable proportion of those with vision impairment. Based on the findings, we outline a framework for how eye tracking can be used to test visual function in the presence of vision impairment.

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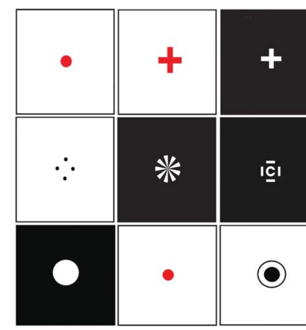

Author Affiliations:
[1]Department of Human Movement Sciences, Amsterdam Movement Sciences and Institute of Brain and Behaviour Amsterdam, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
[2]International Paralympic Committee, Bonn, Germany
[3]Medical Library, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
*w.nieboer@vu.nl

The ever-improving performance and accessibility of noninvasive eye tracking have led to a surge in the use of eye movements to study functional vision across an increasingly broad range of fields. Eye tracking has been used to provide insights into peoples' emotions, intentions, and how skills and knowledge are used. In sports, eye tracking has identified predictive gaze strategies that distinguish the highest-performing athletes in, for example, cricket,[1] whereas in e-sports, experts playing Dota, a complex multiplayer video game, can be distinguished by their greater rate of fixations toward vital in-game information than novices, who fixate more on less imperative areas of interest.[2] In medicine, eye tracking is used to provide feedback to medical students to aid in skill acquisition when learning new surgical skills by teaching more expert-like gaze strategies.[3] In aircraft pilots, eye tracking has been used to show that pilots are better able to stabilize an aircraft in a simulator during landing approach when pilots visually attend the primary flight instruments more.[4] Commercially, webpage designs are optimized on the basis of knowing how consumers scan a webpage when impulsively ordering goods online. Eye tracking is having a significant impact on a variety of fields of expertise.

In medical research, eye tracking has been used to reveal abnormalities in the visual function of people caused by a range of different medical disorders. For instance, it has been shown that smooth pursuit gain—the ability to track a moving target with the eyes—is diminished in schizophrenia.[5] With the use of state-of-the-art eye-tracking technology today, smooth pursuit performance is now considered to be a reliable biomarker of schizophrenia.[6,7] Eye tracking is applied in a similar fashion to aid in the diagnosis of other neuropsychological and neurological disorders such as autism, multiple sclerosis, Parkinson disease, and brain injury.[8–11] Furthermore, eye movement recordings have been used diagnostically to classify different forms of nystagmus for nearly 50 years.[12] Accordingly, eye tracking has become a promising tool to diagnose a range of medical conditions in clinical populations.

Given how useful eye tracking has proven to be for the assessment of functional vision in a variety of neuropsychological and neurological disorders, it stands to reason that it should also hold promise to evaluate the functional consequences of vision impairment. For instance, peripheral vision loss (e.g., in glaucoma and retinitis pigmentosa) is likely to impact saccadic behavior given that saccades are driven by peripheral vision.[13–15] Conversely, central vision loss (e.g., in age-related macular degeneration) will likely impact other eye movement behaviors such as fixations and smooth pursuit, given that fixation and pursuit typically serve to keep the image centered on the fovea. Thus, eye tracking has the potential to provide important insights into the functional consequences of an individual's vision impairment beyond the traditional clinical measures of vision (i.e., visual acuity and visual field).

Although eye tracking holds promise for better understanding the functional consequences of vision impairment, the degree to which eye trackers will work in people with vision impairment remains unclear. Eye trackers traditionally determine where a person is looking based on image processing that identifies ocular landmarks such as the pupil and at least one corneal reflection. More recent forms of eye tracking that use neural networks (e.g., the Pupil Labs Invisible; Pupil Labs GmbH, Berlin, Germany) rely on image processing of the eye and surrounding area. The algorithms used are designed for (and even trained on) healthy eyes, and the degree to which they function reliably in the presence of vision impairment is unknown. For any eye tracker that uses image processing, a clear and stable image of the eye is likely required. Some forms of vision impairment can affect the anterior segment of the eye in ways that could adversely influence the ability of the eye tracker to identify specific features from images of the eyes. For example, identification of the pupil or iris might fail in individuals with aniridia who have damage to or loss of part of their iris. Similarly, identification of the corneal reflex might be impacted in individuals with corneal damage or corneal distortion. For the latter, the choice of eye tracker, especially considering whether it relies on pupil-center tracking or incorporates corneal reflection, can significantly influence the degree to which corneal distortion may impact tracking accuracy. For these cases of vision impairment, the result could be an inaccurate or incomplete estimation of the eye position.

Another potential threat to the suitability of eye tracking in individuals with vision impairment is when there is irregular positioning or an unstable image of the eye because of vision impairment during calibration of the eye tracker. During calibration, the direction of gaze is typically estimated using the assumed direction of each eye. Misalignment of the visual axis, for instance, in strabismus, could alter this estimation so that it becomes inaccurate and unreliable. Calibrating each eye while occluding the other can help in some situations, but even if both eyes are calibrated, it is not clear where gaze is directed if the two visual axes are not aligned. This can be particularly unclear in incomitant or intermittent forms of strabismus, where the magnitude of the deviation changes according to the direction of gaze. Similarly, individuals with macular degeneration often adopt one or more preferred retinal loci, an eccentric location on the retina that serves as a pseudo-fovea.[16,17] This new reference frame, from foveal vision to the preferred retinal locus vision, creates an offset in eye position that needs to be accounted for when estimating the direction of gaze. If multiple preferred retinal loci are present, calibration is likely to fail or be inexact. Calibration of the eye tracker also requires stable fixation. Pathological movements of the eyes, as occur, for instance, in nystagmus, will complicate or hinder the accurate calibration of an eye tracker. In some cases, offline or post-hoc calibrations may be necessary (e.g., for infantile nystagmus).[18] Nonetheless, it stands to reason that eye tracking may be indeed complicated, inaccurate, and perhaps even impossible, in the presence of some visual conditions.

Despite the potential complications when tracking the eyes of individuals with vision impairment, it seems, based on recent publications,[19–21] that eye tracking is increasingly being used to evaluate functional vision in the presence of vision impairment. Recent studies have, for instance, reported delayed saccadic latencies in individuals with glaucoma,[13] diminished fixation stability in amblyopic individuals,[20] and reduced performance in pursuing a moving stimulus in those with macular degeneration,[21] when compared with healthy control participants. However, it may be that those studies are evaluating only a subset of people with vision impairment by focusing on those with ocular conditions that are less likely to impact the quality of eye tracking. Moreover, other aspects of testing remain unclear. It is not clear what aspects of functional vision are being tested to assess the consequences of vision impairment, in what conditions this has been successful, and what forms of video-based eye-tracking equipment (e.g., remote vs. mobile, monocular vs. binocular) might be most suitable for doing so. Clarifying these matters will help establish a more standardized approach for evaluating eye movements in individuals with vision impairment and will help identify the areas that need to be addressed in future research to implement such a test.

The aim of this study was to evaluate the degree to which video-based eye tracking can be used to assess visual function in the presence of vision impairment. A systematic review was performed to survey the approaches that have been adopted using video-based eye tracking to track the eye movements of people with vision impairment and the relative success of those approaches. We expected to find an increasing number of studies over recent years given the growing interest in eye tracking, in conjunction with the improving technical capabilities of contemporary eye-tracking equipment available. We focused on the test paradigms that had been adopted and the equipment used, with a longer-term view of establishing an optimal test paradigm for the clinical assessment of eye movements in the presence of vision impairment. Given our interest in developing a test paradigm suitable for use in clinical settings, we focused only on studies that used contemporary video-based eye tracking and excluded specialized techniques such as limbus trackers, scleral search coils, and electrooculography.

METHODS

Literature Review

This review is reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (www.prisma-statement.org).[22]

Search Strategy

To identify all relevant publications, we conducted systematic searches in the bibliographic databases PubMed, Embase.com, and Web of Science (Core Collection) from inception to November 24, 2021, which were later updated to July 1, 2022, in collaboration with a medical information specialist. The following terms were used (including synonyms and closely related words) as index terms or free-text words: "eye movement," "eye-tracking," "visually impaired," "algorithms," and "parameters." The references of the identified articles were also scanned for relevant publications. Duplicate articles were excluded. All languages were accepted. The full search strategies for all databases can be found in the Supplementary Material (Appendix Tables A1 to A3, available at http://links.lww.com/OPX/A697).

Selection Process

Two authors (WN and AG) independently screened all potentially relevant titles and abstracts for eligibility. Differences in judgment were resolved through consensus. Studies were eligible for inclusion if they (i) used video-based eye tracking, (ii) studied individuals with vision impairment, and (iii) used screen-based tasks that did not involve practiced skills such as reading or driving. Thus, we excluded studies if they used other methods to measure eye movements (e.g., limbus trackers, scleral coils, electrooculography), studied individuals with impairments that were not specifically visual (e.g., autism, Alzheimer disease), concentrated specifically on perimetry or involuntary eye movements (e.g., optokinetic nystagmus, microsaccades), studied rehabilitation or eye movement training, and used certain publication types: editorials, letters, legal cases, interviews, and other nonempirical studies. If necessary, the full-text article was checked for the eligibility criteria. We avoided studies on practiced skills such as reading and driving because gaze was likely to differ based on the skill level of the participant.[23] Eye movement perimetry was not included because, in those studies, eye movements are typically measured as a means to evaluating another construct (visual field size). Involuntary eye movements such as optokinetic nystagmus and, to some extent, microsaccades were not included because we wanted to focus on more goal-directed behaviors.

Data Assessment

The full text of the eligible articles was obtained for further review. The same two authors independently evaluated the methodological quality of the full-text articles using the quality assessment tool for Strengthening the Reporting of Observational Studies in Epidemiology (STROBE).[24]

RESULTS

Search Results

The literature search unearthed a total of 5794 references: 2632 in PubMed, 1915 in EMBASE, and 1247 in Web of Science. After removing duplicates, 4061 references remained. Analysis of the initial screening resulted in a Cohen κ of 0.75. A total of 213 articles remained after screening the title and abstracts for relevance. The full texts of those 213 articles were assessed for eligibility; this resulted in 41 eligible articles for the qualitative synthesis. The flowchart of the search and selection process is presented in Fig. 1. Most studies, approximately 76%, were published within the last decade.

Classification of Articles

Five distinct test paradigms were identified in the eligible articles as being commonly used to assess visual function with eye tracking: (1) fixation stability, (2) smooth pursuit, (3) saccades, (4) free viewing, and (5) visual search. We systematically address each of these five paradigms in the following segments of the Results section of this article.

Paradigm I: Fixation Stability

Study Characteristics

A total of 15 studies were identified that used video-based eye tracking to assess fixation stability in individuals with vision impairment (see Appendix A4, available at http://links.lww.com/OPX/A697). Ten studies reported findings from individuals with central field loss due to juvenile or age-related macular degeneration. The remaining studies that did not study individuals with macular degeneration studied individuals with binocularly discordant visual experience due to strabismus (n = 2), anisometropia (n = 1), or amblyopia (n = 3).

For those studies that explicitly reported the proportion of participants for whom usable data were available, eye tracking in those studies resulted in usable data in at least one eye for all participants (n = 60). For those studies that did not specify the proportion of participants with usable data, data were presumed usable for all of the 320 participants.

It should be noted that all 15 studies examined people with impaired visual acuity, with visual acuity ranging from 0.3 to 0.89 logMAR. None of the studies included people with impaired peripheral vision.

Eye-tracker Characteristics

Details about the eye trackers used in the studies are summarized in the table in Appendix A4, available at http://links.lww.com/OPX/A697. An EyeLink (SR Research Ltd., Ottawa, Canada) was the eye tracker used for most of the studies (n = 9). Under ideal circumstances, the EyeLink 1000 (SR Research Ltd.) can sample eye movements at a rate of 1000 Hz (for one eye). The second most used eye tracker was an SMI (n = 4; SensoMotoric Instruments GmbH, Tellow, Germany). Overall, the sample rate ranged from 50 to 500 Hz when reported (n = 11).

None of the studies reported difficulties calibrating the eye tracker. For a part of the analysis, Tarita-Nistor et al.[25] excluded five age-related macular degeneration patients with very low visual acuity—average 1.22 logMAR in the worse eye—because this subgroup was not able to fixate on the target (3° cross), resulting in exceptionally variable fixation for the worse eye. The results of the better eye were considered.[25] Shaikh et al.[26] excluded 10 amblyopic subjects with latent nystagmus beforehand because this condition would interfere with the analysis of the fixation stability data.

Description of the Paradigm(s)

The fixation paradigms were straightforward in that participants were instructed to simply fixate on a static target. The target could vary in shape (most commonly a disc/circle or cross), size, and color. It could be displayed for various durations, and the background color could also vary (Fig. 2). The target size ranged from 0.3 to 5°, with the smaller targets more commonly used in impairments of binocular vision (e.g., strabismus, amblyopia). The two exceptions in stimulus shape (Fig. 2) were a square-wave radial grating target used by González et al.[27] and a Landolt C target used by Macedo et al.[28]

The paradigms adopted by Bellmann et al.[29] and Bethlehem et al.[30] differed from the regular fixation paradigms by using peripheral anchor points for fixation (Fig. 2, second row). Their paradigms used four anchor points at the corners of an unmarked square to test the fixation of individuals with age-related macular degeneration[29] and juvenile macular degeneration (JMD).[30] Participants were

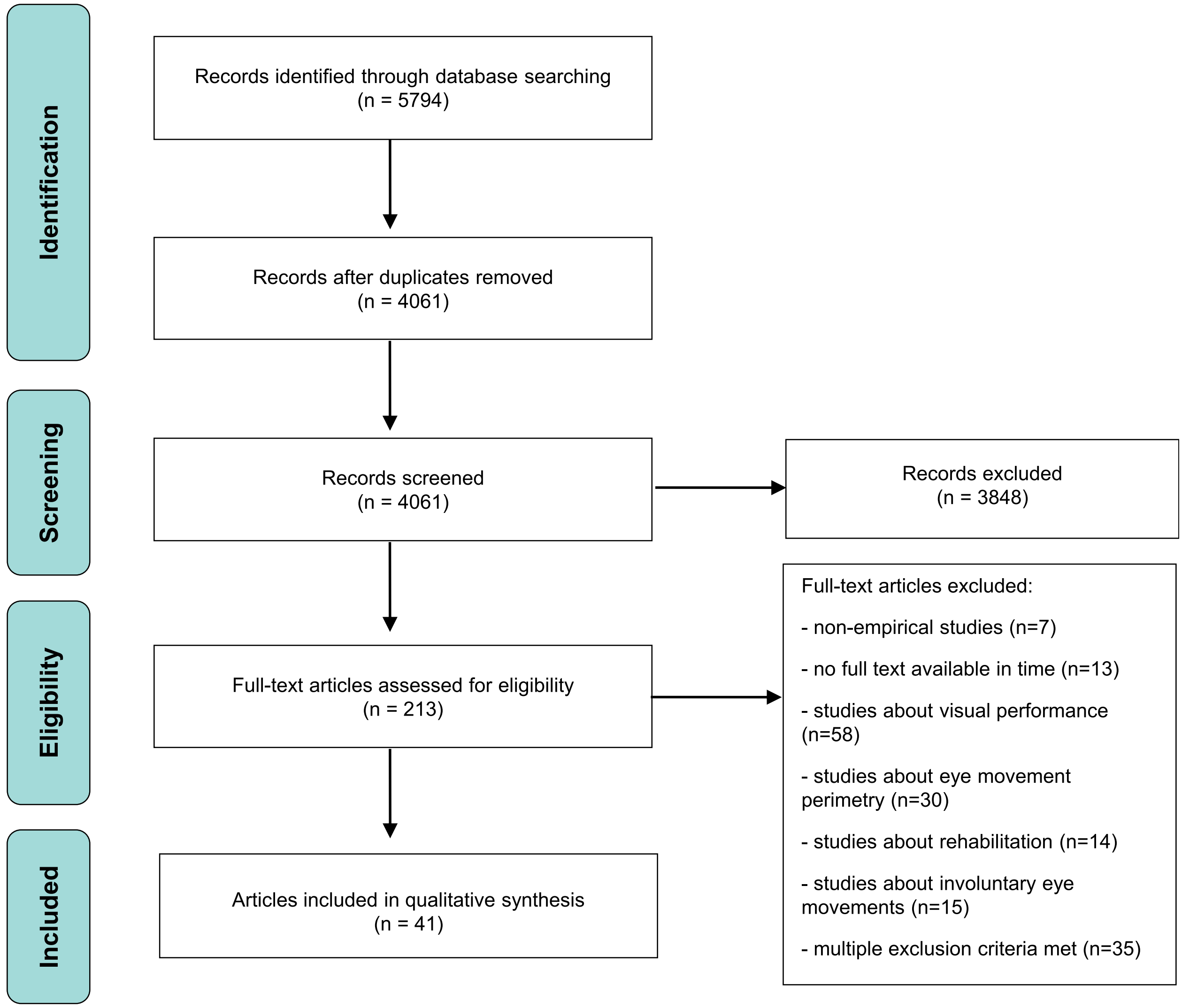

FIGURE 1. Flowchart of the search and selection process.

instructed to direct their central fixation toward the center of the four anchor points rather than using one central target. However, in age-related macular degeneration patients, fixation was more stable for a single central target than when using the anchor points[29]; this has not been studied for JMD patients or individuals with a newly developed central scotoma.

Even though during daily life people use both eyes, most studies examining individuals with macular degeneration tested only the eye with better visual acuity under monocular viewing conditions (n = 8; Appendix A4, available at http://links.lww.com/OPX/A697). One study that did consider binocular viewing found that, when compared with monocular conditions, fixation stability in the worse eye of age-related macular degeneration patients improved during binocular viewing. The stability of the better eye remained unchanged.[25] The results from Tarita-Nistor et al.[25] suggest that fixation is driven by the better eye in binocular viewing. The authors also concluded that differentiating between the worse and better eye is necessary if interested in correlating fixation stability and visual acuity. Therefore, the results for the better eye are preferred when measuring fixation stability in individuals with macular degeneration.

The main outcome measure in all studies was the bivariate contour ellipse area, which is the area of an ellipse that encompasses a given proportion of fixation points during a fixation trial. Fixation stability can be quantified using this measure; a smaller bivariate contour ellipse area represents more stable fixation.

Effects of Vision Impairment on Fixation Stability

Macular Degeneration

Fixation stability is significantly impaired in individuals with macular degeneration. This instability is suggested to partially be a result of the reduced acuity in the preferred retinal locus in comparison with a normal fovea.[25,30–34] In JMD patients, the reduced visual acuity led to an increase in the presence of unwanted sporadic saccades, suggesting a disability to keep the eye fixated on a target.[30] This is in line with the findings of Tarita-Nistor et al.,[25] where those in the age-related macular degeneration subgroup with the most reduced visual acuity were unable to use their central vision to locate the target, leading to increased fixation instability. The fixation instability might also be driven by ineffective involuntary eye movements

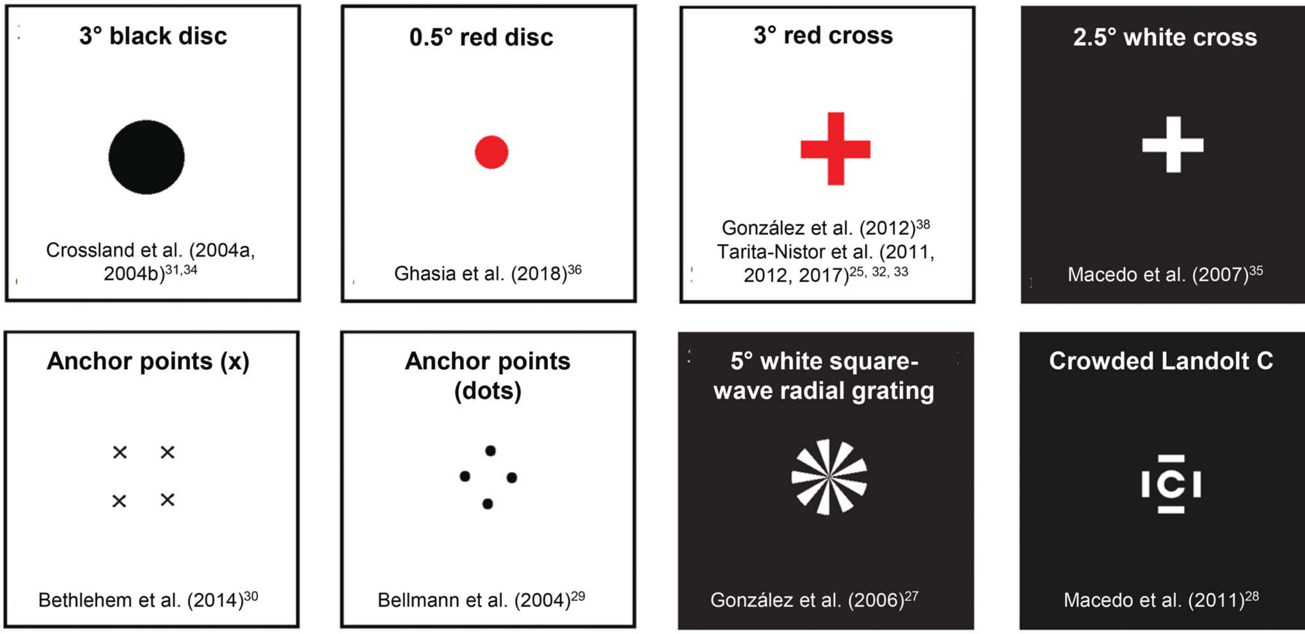

FIGURE 2. Selection of variations in the target (not scaled) among the identified fixation stability paradigms.

(e.g., drifts) because of reduced oculomotor control in the peripheral retina where the preferred retinal locus is located.[28,30,35]

Impairment of Binocular Vision

Fixation stability is impaired in (pediatric) individuals with strabismus, independent of the presence of amblyopia and latent nystagmus.[36,37] Fixation instability was larger in the deviated eye, and this instability worsened with the presence of amblyopia and as the angle of strabismus increased.[36,37] It has been argued that this fixation instability in strabismus is due to the increased amplitude of involuntary eye movements such as drifts and microsaccades.[36,37]

Similar results were found in amblyopic patients, where fixation stability was impaired, more so in the amblyopic eye, and with the amount of instability increasing commensurate with increases in the severity of the amblyopia.[20,26,38] This instability was accompanied by increased velocities and amplitudes of fixational eye movements such as drifts and (micro)saccades.[20,38]

Paradigm II: Smooth Pursuit

Study Characteristics

A total of four articles were identified that used eye tracking to assess smooth pursuit in individuals with vision impairment (Appendix A4, available at http://links.lww.com/OPX/A697). Two patient groups were studied: macular degeneration (n = 3) and anisometropic amblyopia (n = 1). No studies assessed smooth pursuit in people with peripheral visual field impairment. None of the studies explicitly reported the proportion of participants for whom usable

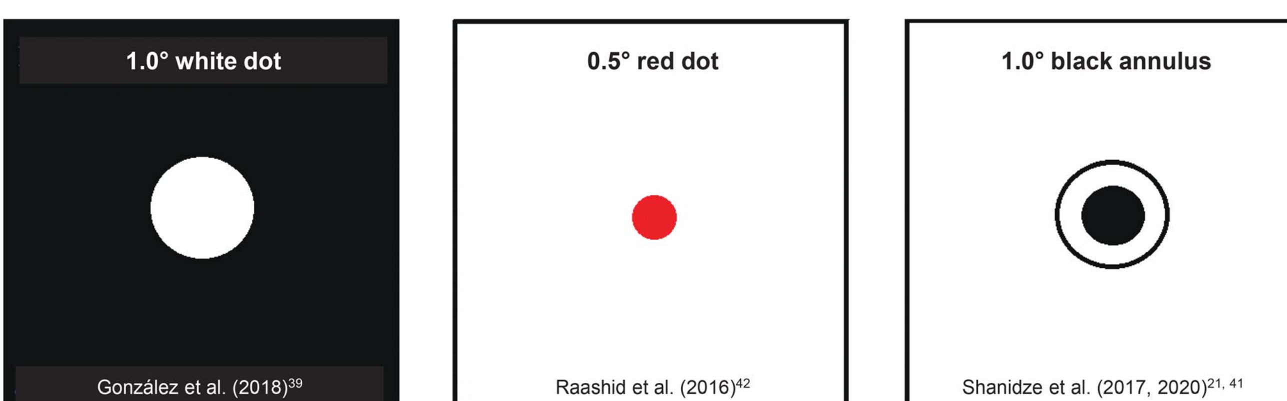

FIGURE 3. Variation in target parameters (not scaled) among the identified smooth pursuit paradigms.

eye-tracking data were available; therefore, data were presumed usable for all participants (n = 36).

Eye-tracker Characteristics

All four studies used a different eye tracker (Appendix A4, available http://links.lww.com/OPX/A697), with three of the four eye trackers being mobile (head-mounted) and the other using the EyeLink 1000.

There was one reported limitation regarding the use of an eye tracker. González et al.[39] could include only participants who were able to see the target without corrective lenses because the El Mar 2000 (El Mar inc., Toronto, Canada) eye tracker was not able to detect the pupil when the participants wore corrective lenses. The effect of blur (if lenses were removed) on smooth pursuit due to refractive errors is unknown.[39]

Description of the Paradigm(s)

In smooth pursuit paradigms, participants were instructed to follow a moving target shown on a screen. All articles adopted a step-ramp paradigm where a stimulus was presented at the center of the screen for 1 to 1.5 seconds before it disappeared and reappeared at a random "step" location 4 to 10° horizontally or vertically from its original location. In the "ramp" portion of the paradigm, the stimulus moved at a constant velocity along a trajectory in the opposite direction of the step. The step was introduced by Rashbass[40] to account for the latency of smooth pursuit. It serves as a visual cue to initiate smooth pursuit eye movements in response to a moving target, with the step helping to reduce the occurrence of catch-up saccades, helping to show that velocity is the driver of smooth pursuit rather than position.[40]

The primary measure of performance in all studies was the smooth pursuit gain, calculated by dividing the eye movement velocity by the stimulus velocity, with a gain of 1 representing perfect pursuit. Pursuit target velocities ranged from 5 to 30° per second. Pursuit targets differed in size, 1°[21,39,41] or 0.5°[42]; color, white[21,39,41] or red[42]; and shape, type of dot (Fig. 3).[39,42]

Effects of Vision Impairment on Smooth Pursuit

Macular Degeneration

Smooth pursuit is impaired in people with macular degeneration.[21,39,41] The pursuit strategies adopted by individuals with macular degeneration showed high variability due to differences in scotoma(s), characteristics, and variations in the binocular overlap of the scotomas.[34] For those with overlapping scotomas, smooth pursuit gain was influenced by the direction of the target relative to the scotoma—whether it moved toward and into the scotoma or started in and moved away from the scotoma.[34] Shanidze et al.[41] also found that both stereoacuity and contrast sensitivity had an impact on the coordination between the eyes, quantified as between-eye correlations, as well as on monocular smooth pursuit gains. These results suggest that the smooth pursuit performance of individuals with macular degeneration is dependent on the availability of visual input to both eyes, but also that the binocular coordination of the eyes may be disrupted with asymmetrical visual field loss.[34] The asymmetrical visual field loss resulted in differences in contrast sensitivities between the eyes.[34] This difference in visual function between the two eyes led to a situation where the eyes moved more independently from each other.[34] In a screen-based paradigm, participants did not compensate for this reduced smooth pursuit gain by making more head movements.[21] The severity of the smooth pursuit impairment was dependent on the direction of the target relative to the location of the central scotoma and the adopted preferred retinal locus.[21,41] González et al.[39] did not find a relationship between the smooth pursuit performance and the direction relative to the preferred retinal locus used for fixation but suggested that individuals with macular degeneration adapt to the task by using a different preferred retinal locus that is more suitable.

Amblyopia

The single study looking into anisometropic amblyopia found no difference between the gains of amblyopic and control participants.[42] However, there was significantly more variability in the gains of the amblyopic group.[42] The main finding was that the latency of smooth pursuit initiation was significantly prolonged when viewing with the amblyopic eye and that this was not related to the severity of the amblyopia.[42] It was argued that this might be a result of motion detection deficits or reduced contrast sensitivity, both of which could delay signals from the target.[42]

Paradigm III: Saccades

Study Characteristics

We identified eight studies researching saccades in low vision (Appendix A4, available at http://links.lww.com/OPX/A697). The studies examined participants with glaucoma (n = 3), amblyopia (n = 3), hemianopia (n = 1), and JMD (n = 1).

In studies where the proportion of participants with available usable data was explicitly stated, eye tracking yielded usable data for all participants (n = 26). In cases where the proportion of participants with usable data was not specified, it was assumed that all participants had usable data (n = 97).

Eye-tracker Characteristics

Five different eye trackers were used across the eight studies (Appendix A4, available at http://links.lww.com/OPX/A697). All three studies involving amblyopic participants used the Chronos Vision (Chronos Vision GmbH, Berlin, Germany). The EyeLink 1000 was the second most used eye tracker (n = 2).

Giacomelli et al.[43] reported difficulties calibrating the Tobii Pro-2 (Tobii AB, Stockholm, Sweden) eye tracker on participants with JMD. The procedure had to be repeated several times because of the unstable eccentric fixation, although correct calibration was eventually achieved in all participants.[43] No other major limitations were reported, with eye tracking presumably resulting in usable data from all participants (n = 123).

Description of the Paradigm(s)

To elicit saccades, most studies adopted the *step* paradigm in which a static stimulus at the center of the screen acted as an initial fixation target. In that paradigm, the target disappears and then reappears on the screen at a random position displaced horizontally, vertically, or diagonally from the initial fixation location, with an eccentricity ranging from 5 to 20°. Participants were instructed to make a saccade toward the new location of the target. Typically, the target after moving was displayed for 1 to 3 seconds before disappearing and reappearing at the center of the screen to initiate a new trial. Targets were dots that were not larger than 1.5° and were mostly white on a black background.

There were a few variations to the typical procedure. In the *gap* paradigm,[13,15] to reduce saccadic latency, the reappearance of the target was delayed for approximately 200 milliseconds so that there was an interval in which there was no target. The *overlap* paradigm[44] is somewhat the opposite, where the fixation target remains at the moment that the new target appears, resulting in a brief period with two targets on display. In the *double-step* paradigm,[45] the fixation target disappears and reappears eccentrically, but as soon as the eye starts moving, the target shifts back toward the central fixation location (the "second step"). This paradigm reportedly assesses the adaptability of saccades to moving targets.

In the study by Lamirel et al.,[14] for a second task (where the first task was the step paradigm), participants had to make a saccade toward a moving target rather than a static target. In this paradigm, when the fixation target was removed, participants were required to produce a saccade to a target 7° from the initial fixation target and to track this target that was moving horizontally or vertically toward the initial fixation target with a constant velocity of 2, 5, or 10° per second.[14] In this task, glaucoma patients were unable to inhibit reflexive saccades toward the target before the signal was given, resulting in a rejection of 35% of the trials.

Effects of Vision Impairment on Saccades

Glaucoma

Compared with control participants, individuals with glaucoma had delayed saccadic latencies, saccades with lower (peak) velocities, and hypometric saccades (i.e., gain <1, undershooting the target).[13–15] Interestingly, the saccades performed by people with normal-tension glaucoma were the most affected.[13] The saccadic deficits were suggested to be a result of an impairment to the neural network that effectively locates a target and then programs and executes the saccade.[13–15] Impaired motion perception in primary open-angle glaucoma was suggested to be the underlying cause of prolonged saccadic latencies toward a moving target.[14]

Amblyopia

The saccades performed by anisometropic amblyopes had prolonged and more variable latencies, but amplitudes and velocities that were comparable to control participants.[45,46] This suggests that visual processing is slower, but that the execution of saccadic motor programs is unaffected; it was hypothesized that the deficits in fixation stability that were also found for this group might also be associated with the prolonged saccadic latency.[46] Latencies and amplitudes of saccades were affected in strabismic amblyopes, and in contrast to anisometropic amblyopes, latency deficits were dependent on visual acuity, and the precision of the saccades was dependent on stereoacuity.[46,47] In both groups, there was no advantage for the timing of saccades when viewing binocularly when compared with fellow eye viewing.[46,47]

Hemianopia

Saccades were quantified and reported in only four participants with hemianopia. In their study, Fayel et al.[44] found that, despite the hemifield loss, individuals with hemianopia appeared to unconsciously perceive the target and were able to make saccades toward it in their contralesional hemifield. However, these saccades had prolonged latencies and smaller amplitudes than in control participants.[44] A disruption in signal transmission between the saccade-generating cerebral structures was suggested as an explanation for these changes.[44]

Juvenile Macular Degeneration

Only Stargardt disease has been examined, with the binocular saccadic movements guided by eccentric fixation having significantly lower velocities than control participants. This effect was more pronounced when the location of the target corresponded with the retinal area(s) underlying the scotoma and might have been exacerbated by reduced contrast sensitivity in the preferred retinal locus.[43]

Paradigm IV: Free Viewing

Study Characteristics

A total of six studies were identified that used eye tracking to assess free-viewing behavior in individuals with vision impairment (Appendix A4, available at http://links.lww.com/OPX/A697). The participants in each study had visual field loss due to glaucoma (n = 3 studies), retinitis pigmentosa (n = 2), or hemianopia (n = 1).

For those studies that explicitly reported the proportion of participants for whom usable data were available, eye tracking resulted in usable data for 42 of the 53 participants, where 11 had to be excluded in one study because of eye tracker–related difficulties. For those studies that did not specify the proportion of participants with usable data, data were presumed usable for all the 70 participants.

Eye-tracker Characteristics

Most studies used an EyeLink eye tracker (n = 4; Appendix A4, available at http://links.lww.com/OPX/A697). Gestefeld et al.[19] excluded the data of 11 of the 31 glaucoma patients and 12 of the 32 control subjects because the EyeLink 1000 eye tracker failed to detect the pupil or corneal reflection and was thus unable to continuously measure the gaze position. The eye-tracker difficulties were caused by participants having drooping eyelids or using corrective lenses.[19] In addition, the calibration procedure in that study in some cases had to be repeated several times, typically adjusting the setup each time to minimize factors such as reflections from the lenses.[19] It was reported that it could take up to 25 minutes to prepare the participant and calibrate the eye tracker. The authors commented that, if the goal is to use eye tracking in clinical practice, this preparation time should be reduced significantly.[19]

The use of trial lenses in frames to correct vision can pose an additional problem when comparing groups because the trial frame positioned in front of the eyes can restrict the visual field. Therefore, in the study by Smith et al.,[48] all participants wore a trial frame, regardless of whether a correction was needed or not, to make sure that each participant had the same limitation.

The 50-Hz sample rate of the eye tracker used by Pambakian et al.[49] was reported as a limitation for the calculation of saccadic parameters such as the peak velocity and saccade duration. All other studies sampled at least 200 Hz.

Description of the Paradigm(s)

In the free-viewing paradigm, participants were instructed to watch a video clip or images of particular scenes as they typically might do. The procedure is passive, thus giving no specific task instructions about where the participant should look. The studies that used images displayed photographs of natural or urban scenes for 3 to 6 seconds.[48–51] Gameiro et al.[51] changed the image size to compare free-viewing behavior for images that covered either both the residual and affected visual fields, or only the residual visual field. Pambakian et al.[49] filtered out high spatial frequencies to reduce details from the images and presented both the filtered and unfiltered images. Filtered images, devoid of salient features, were able to accentuate the differences in eye movements between people with hemianopia and control participants during free viewing.[49]

Video clips with a duration of 1 to 7 minutes were used, typically displaying everyday footage of traffic, motion pictures, nature documentaries, or animated films.[19,52]

The dependent variables that were extracted from the data were typically the number of saccades and fixations, fixation durations, saccadic amplitudes, saccadic velocity, and the scan path—the path followed by the participant's eye when observing a scene.

The Effects of Vision Impairment on Free-viewing Behavior

Glaucoma

The effects of glaucoma on free-viewing behavior remain unclear. Smith et al.[48] found that glaucoma patients, when compared with control participants, made fewer saccades per second and consequently had longer average fixation durations when watching images of natural scenes. However, there was no difference in the fixation duration or rate when watching video clips in either monocular or binocular viewing, nor in the saccadic amplitudes or saccadic velocity.[19] In contrast, Asfaw et al.[50] showed that saccades were smaller in amplitude when viewing with the worse glaucomatous eye. The spread of fixations was smaller compared with both control participants and in the better eye.[48,50] This nature of the changes correlated with the patient's visual field loss in one study[50] but not in another.[48] These inconsistencies are addressed in the Discussion section shortly.

Retinitis pigmentosa

There was little difference in the free-viewing behavior (i.e., number of fixations, fixation duration, and saccadic amplitude) of individuals with retinitis pigmentosa when compared with control participants.[51] It was suggested that the lack of group differences might have been a result of each individual with retinitis pigmentosa having developed their own scanning strategy specific to their vision loss, as was reflected by the high variability in behavior in the retinitis pigmentosa group.[51] In another study, the gaze of late-stage retinitis pigmentosa patients was dispersed significantly less than for healthy control participants, driven largely by a reduction in the number of eye movements, which was suggested to be a result of the restricted peripheral field in retinitis pigmentosa.[52] In contrast, gaze dispersion was similar between early-moderate retinitis pigmentosa patients and control participants, although the retinitis pigmentosa patients seemed to have compensated by performing more head movements rather than eye movements given that a head-mounted eye tracker was used that allowed head movements.[52]

Hemianopia

Only one study has investigated free-viewing behavior in hemianopia. In their study, Pambakian et al.[49] found that homonymous hemianopic patients made significantly more fixations of shorter duration compared with control participants when viewing filtered but not unfiltered images. Irrespective of the filtering, scan paths were significantly longer for patients.[49] In addition, patients made more saccades of shorter duration and smaller amplitude into their blind hemifield compared with the seeing hemifield.[49] In contrast to the other impairment types (retinitis pigmentosa, glaucoma), the fixations in hemianopia were more widespread, covering more area of the image than for control participants.[49] The results were related to lesion age, with more widespread fixation patterns for those whose lesion was older than 6 months. The results were not related to the size or location of the loss, suggesting that they reveal the compensatory eye movement strategies that are developed.[49]

Paradigm V: Visual Search

Study Characteristics

A total of eight studies that used eye tracking to assess visual search behavior in individuals with vision impairment were identified (Appendix A4, available at http://links.lww.com/OPX/A697). The patient populations included individuals with macular degeneration (n = 5), glaucoma (n = 3), retinitis pigmentosa (n = 1), and amblyopia (n = 1; children aged 5 to 15 years).[53]

Among studies that explicitly reported the proportion of participants for whom usable data were obtained, eye tracking produced usable data for 74 of the 93 participants. For studies where the proportion of participants with usable data was not specified, data were presumed usable for all participants (n = 115).

Eye-tracker Characteristics

The EyeLink was again the most frequently chosen eye tracker (n = 5; Appendix A4, available at http://links.lww.com/OPX/A697). Taylor et al.[54] reported difficulties obtaining a good calibration with the EyeLink II with some patients with age-related macular degeneration because of the eccentric fixation. It was assumed that the accuracy of the eye tracker was poorer for those age-related macular degeneration patients than for the control participants; therefore, the analysis was done twice, once by considering all patients and once by considering only patients whose calibration was rated as "good" by the eye tracker's software.[54] Age-related macular degeneration patients with a good calibration made significantly fewer saccades per second compared with the healthy controls, whereas this outcome did not reach significance when considering all age-related macular degeneration patients—the outcome of the two analyses did not differ for the other eye movement parameters.[54]

Also in age-related macular degeneration, Thibaut et al.,[55] using the SMI iView-X, excluded four age-related macular degeneration patients because more than 25% of the eye movement data were missing because of signal loss as a result of excessive head movements. In their later study, Thibaut et al.[56] excluded 15 of 32 patients and 2 older healthy control subjects again because of excessive head movements (SMI Red-m). The head was unrestrained during testing.

Chen et al.[53] sought to establish the impact of nystagmus on visual search performance using the EyeLink 1000 and reported no difficulties in the calibration or data acquisition.

Description of the Paradigm(s)

In the visual search paradigms, participants were typically instructed to find a target among a set of distractors or within a crowded scene. A target could be an abstract item that differed from distractors in some respects, such as an "O" among Landolt C's,[57,58] or a specified object or patch within a photograph of a natural scene.[54,56,59,60] In a study by Chen et al.,[53] children had to find the difference between two engaging photographs displayed next to each other, where some features present in one photograph were absent from the other. The dependent variables were typically the search time, number of errors, number of fixations (or saccades), fixation duration, saccadic amplitude, or saccadic velocity.

A consideration that has been raised in several articles is that uncertainty and bias can be a concern when participants are required to produce a manual (e.g., space bar or mouse click) or verbal response to indicate that they have found the target. Individuals with vision impairment might require additional time to locate and then verify that they have found the target, whereas control participants might be more confident and respond at first glance. In addition, in some paradigms, participants were required to move the mouse to click on the target, which could be challenging for patient groups given the additional need to locate and follow the cursor. These effects could result in increased search times in patient groups compared with control participants for reasons not related to their ability to find the target.

The Effects of Vision Impairment on Visual Search Behavior

Glaucoma

The total number of fixations and the search times were larger in glaucoma patients than in control participants, whereas the number of saccades per second was lower.[57,59] The number of fixations and the search times increased with increasing visual field loss.[57] The lower saccade rate that might be responsible for longer search times in Smith et al.[59] was found to be related to the reduced contrast sensitivity and thereby to the severity of the visual field loss. Wiecek et al.[60] found no change in any eye movement dynamics (i.e., size, frequency, and duration of saccades and fixations) but did find that there were fewer eye movements toward the locations of the field loss.

Macular degeneration

Visual search performance was worse in individuals with macular degeneration compared with control participants. Average search duration was significantly longer, and patients made more mistakes.[54–56] This was more so if the object had to be localized in a crowded rather than a sparse scene.[56] The eye movements were also different: the saccadic amplitude was smaller, and there were more saccades per second and fewer return saccades to refixate on a previous point of interest.[54,55,57,58] Visual search performance was poorer with worse visual acuity and increasing lesion size,[54,56] with visual acuity and lesion size also associated with the number of (return) saccades.[55,57] It was suggested that a combination of the size of the central scotoma and the reduced visual acuity in the preferred retinal locus can explain the impaired visual search behavior.[58]

Amblyopia

Results from a single study showed that visual search performance was compromised in amblyopic patients. Search accuracy was poorer, and search times were longer than in control participants, with performance decreasing further with increases in disease severity.[53] The decreased performance was accompanied by a decrease in the number of saccades.[53] The presence of latent nystagmus accentuated these deficits.[53]

STROBE Quality of Reporting

Fig. 4 displays the results for the 22 items on the STROBE checklist.[24] None of the studies reported a sample size calculation of any sort (item 9). Except for one study, no efforts were made to describe the potential sources of bias (item 10). Study limitations were not reported in 29.3% of the studies, and the discussion of the limitations was considered to be insufficient for an additional 12% of studies (item 20). The likelihood of having no study limitations is slim. Minor concerns include the absence of a predefined hypothesis in the Introduction section (41.5%; item 3). These results highlight that the quality of reporting of medical observational studies can be improved. However, the methods and results sections were admirably complete. Based on these results from the STROBE checklist (Fig. 4) and the guidelines provided in Vandenbroucke et al.,[24] reporting of the observational studies included in this systematic review was rated "fair" by the authors.

DISCUSSION

The aim of this article was to establish the degree to which video-based eye tracking can be used to assess visual function in the presence of vision impairment. A systematic review was performed to survey the approaches that have been adopted to track the eye movements of people with impairment and to evaluate the success of those approaches. Results revealed an emerging field of research. We identified a total of 41 articles, with 75% of those published in the last decade and 100% in this century. Analysis of the articles revealed five frequently used tests of visual function: fixation stability, smooth pursuit, saccades, free viewing, and visual search. There was a skew in the types of ocular conditions examined, with studies in glaucoma and macular degeneration being common and studies of conditions that affect the anterior segment of the eye (e.g., cataract, corneal scarring) or the retina (e.g., diabetic retinopathy, retinal detachment) being less common. The studies reported considerable success in generating usable data, with usable data gathered from 96.5% of participants.

Visual function was typically tested using at least one of five common test paradigms: fixation stability (15 studies), smooth pursuit (4 studies), saccades (8 studies), free viewing (6 studies), and visual search (8 studies). The five test paradigms seem complementary to each other. Fixations, smooth pursuits, and saccades are fundamental visual behaviors for many aspects of visual function, such as for maintaining a moving object on the fovea and for shifting gaze between different targets. The free-viewing and visual search paradigms represent higher-order measures of visual function that evaluate how these fundamental visual behaviors are cohesively deployed to process visual stimuli in more complex and naturalistic tasks. For example, the free-viewing paradigm typically evaluates the initial bottom-up processing of visual information, whereas the visual search paradigm investigates top-down search strategies and processes. The role of instructions here is crucial, given that instructions (e.g., to "search for" an object) will lead to a top-down influence and alter scanning behavior.[61] The five paradigms, when used together, allow for a more comprehensive exploration of the underlying mechanisms of visual function and impairment. This approach may pave the way for the development of novel interventions and technologies that can enhance visual outcomes.

Fixation stability was the most frequently studied eye movement behavior in individuals with vision impairment. Fixation stability paradigms typically adopt very simple designs and instructions, yet have been found to provide reliable data about the severity of impairment. The current clinical standard for assessing fixation is the scanning laser ophthalmoscope or the microperimeter, which are typically restricted to the use of small monochromatic targets, monocular viewing, a restrained head, and a fixed viewing distance. These parameters can be varied when instead using eye tracking, giving more control and degrees of freedom. When compared with the scanning laser ophthalmoscope, video-based eye trackers have shown high test-retest reliability for measuring fixation stability and have been demonstrated to be a useful tool for this purpose.[62] Caution is required, though, in altering the nature of the target, given that the target shape and size can affect fixation stability.[63,64] For example, González et al.[38] used a 3° fixation

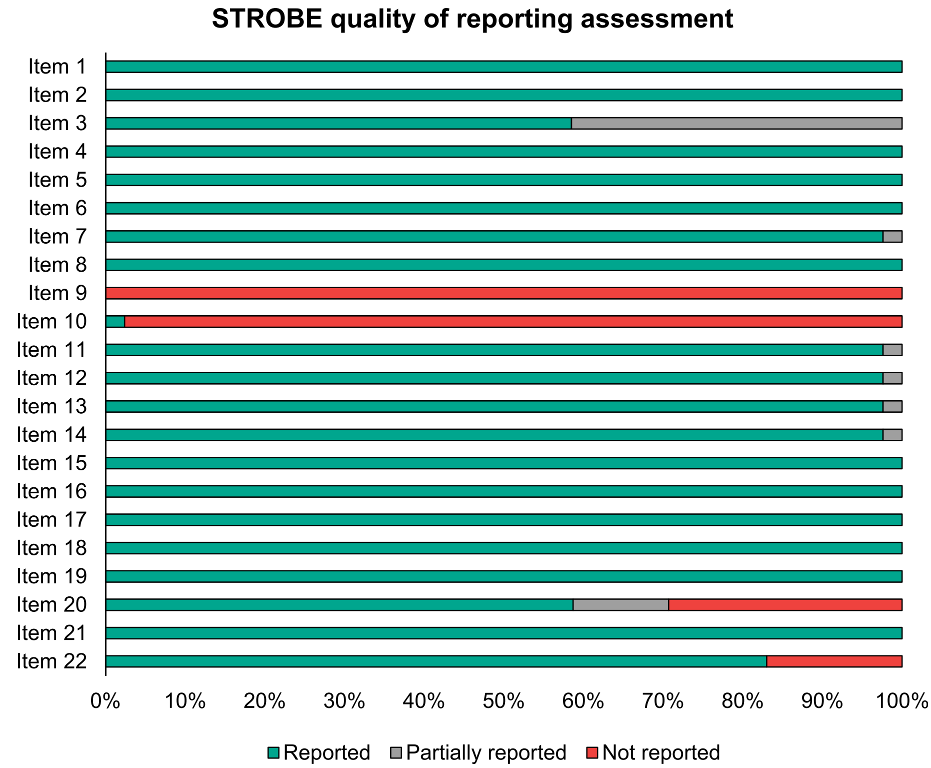

FIGURE 4. The assessment of the quality of reporting using the 22-item checklist: Strengthening the Reporting of Observational Studies in Epidemiology (STROBE). Green bars indicate item reported, yellow indicates partially reported, and red bars indicate not reported.

cross and found lower fixation stability in amblyopes compared with Shaikh et al.[26] when using a 0.5° circular target in the same population. In a study by Thaler et al.,[64] different target shapes were tested on healthy participants, with the results showing that fixation stability varied depending on the target, with a disc-shaped target resulting in the worst fixation stability. This was also evident in strabismic monkeys, where the best fixation stability was achieved using a fixation cross.[63] It is therefore recommended to assess fixation stability using a fixation cross, as has been used by González et al.,[39] Tarita-Nistor et al.,[33] and Macedo et al.[28]

Four studies assessed smooth pursuit in individuals with vision impairment. Although smooth pursuit eye movements occur less frequently than fixations and saccades, the assessment of smooth pursuit has noteworthy clinical relevance. In neurological disorders such as multiple sclerosis and Parkinson disease, smooth pursuit performance when assessed using eye tracking is considered a reliable tool for diagnosis.[11,65] However, much remains to be explored when assessing smooth pursuit in individuals with vision impairment. It remains possible that neurological disorders that manifest in vision impairment such as optic neuritis, cerebral visual impairment, and optic neuropathies may also exhibit distinct deficits in smooth pursuit performance, but further research using eye tracking is needed to investigate this possibility.

Paradigms that test saccadic eye movements are increasingly used to test a range of factors associated with health conditions. Saccade paradigms can be used to discriminate between healthy and impaired eyes, with the results from the saccade paradigms examined in this review consistently showing that saccadic latencies are prolonged in individuals with impairment, including in amblyopia, glaucoma, and hemianopia.[13–15,44–47] Saccade paradigms also offer a more objective way to map the visual field using saccadic latencies in individuals with visual field loss[66,67] or to assess the responsiveness of individuals with mild traumatic brain injury.[68–70] Saccadic latencies are particularly likely to be used when testing impairment, but also other saccade metrics are interesting for rehabilitation purposes, including antisaccades and memory-driven saccades.[70]

In contrast to the more basic test paradigms, the tests of free viewing and visual search gave different results depending on the specific task constraints. In the case of the free-viewing tests, there were several characteristics of the images and video clips that were difficult to control for but might have influenced eye movement behavior, especially in the presence of vision impairment. For instance, brightness and contrast levels can vary greatly between different images or video clips, particularly in scenes captured during daytime or nighttime, or in different weather conditions. Those factors, if not controlled, may influence the results of participants whose impairment renders them sensitive to light or reduces their contrast sensitivity.[42,71,72] Pambakian et al.[49] studied gaze using the same images twice, once in full detail and once when low-pass filtered to reduce the details. They found that abnormalities in gaze behavior were more pronounced for the filtered images. The salience of objects is another important factor that influences bottom-up processes that drive (saccadic) eye movements when viewing those images. Reduced salience (e.g., by filtering an image) can also reduce the number of eye movements.[52] The effect of a salient object depends on the type of scene. For example, an elephant grazing on an empty savanna might not require large saccades or long fixations to adequately comprehend the content of the scene. Similarly for movie clips, the main character is usually located centrally, and so the eyes are not drawn to the corners of the screen or to the borders of the visual field. Gestefeld et al.[19] found that video clips that contain highly dynamic content, such as animated films, are the most suitable to separate patients from control participants based on eye movements. Therefore, images and videos with salient features scattered over the scene, or (filtered) scenes without predictable scan paths, seem to be the most suitable for the assessment of free-viewing behavior in the presence of vision impairment.

Differences between the visual search paradigms resulted in different test outcomes in glaucoma patients. Coeckelbergh et al.[57] found that glaucoma patients made more fixations but similar saccade size and frequency during visual search as healthy participants when using an abstract visual search paradigm where an O had to be located among a set of Landolt C's. In contrast, Smith et al.[59] found that glaucoma patients made fewer saccades but similar fixation frequency and duration as healthy participants using a search paradigm where participants had to locate a specific object within a natural scene, and Wiecek et al.[60] found no changes in any eye movement parameters using a search paradigm where participants had to locate a specific patch of an image within a natural scene. In contrast to the target in the study by Smith et al., the image patch used by Wiecek et al. had randomized contrast and rarely contained recognizable objects. This choice was made to minimize the role of top-down factors and thus rely more on feature saliency.[60] However, as mentioned, a lack of saliency can reduce the number of eye movements, which might make it difficult to detect abnormalities in eye movements.[52] Differences between results can be explained by differences in stimuli (optotypes vs. natural images). Smith et al.[73] compared performance when searching for a Landolt C with performance when searching natural images and only found significant differences in search times between glaucoma and control participants when searching for an object within the natural images. Although Coeckelbergh et al.[57] did find significant differences in search times using the Landolt C, this was only apparent for subjects with severe visual field restrictions (average, 34 ± 23° horizontally) and not for visual fields greater than 80° in diameter. Therefore, a visual search paradigm in which individuals with vision impairment are required to find an object in a natural scene is recommended, whereas for the more severe cases of vision impairment, a more abstract paradigm might also be suitable.

The testing of eye movements proved to be possible during each of the tests irrespective of the type of vision impairment being tested. In the tests of fixation stability, only 5 participants (of 380; 1.3%), all from a single study, had to be excluded for at least a part of the analysis. Those five individuals had age-related macular degeneration, with a mean visual acuity of 1.22 logMAR in their worse eye, and were not able to maintain fixation on the 3° fixation cross using that eye.[25] Shaikh et al.[26] excluded 10 amblyopic patients because of latent nystagmus, with the inference being that the nystagmus influenced the quality of the eye tracking. When testing binocularly or with the better eye, all participants across all studies were able to successfully perform the tests of fixation stability, smooth pursuit (36 participants), saccades (123 participants), free viewing (112 participants), and visual search (199 participants). Taken together, only 30 of a total of 870 participants with vision impairment in all studies were excluded, resulting in a success rate of 96.5%. However, 30 of 232 participants with vision impairment (12.9%) were excluded from analyses in those 12 of 41 studies that explicitly reported the proportion of participants with usable data (e.g., due to problems with calibration of the eye tracker). In those studies that did not report the proportion of participants with usable data, it was assumed that usable data were available for all of the 638 participants. It remains possible that, in those studies, calibration might have been difficult or indeed not possible for some participants, but that those data were not reported. For instance, some studies might have used inclusion criteria that required participants to have acceptable calibration to take part, which could inadvertently result in an omission of such information. As a result, the data available here for the proportion of participants with usable data might be lower. The variability in reporting practices makes it challenging to precisely assess the impact of such exclusions on the reported outcomes. This emphasizes the importance of promoting transparency in future studies by providing clear information about excluded participants and potential methodological limitations.

The high success rate found in this study when testing individuals with vision impairment highlights the potential that eye tracking has as a tool for assessing visual function in those with impairment; however, it might also reflect the selectiveness of the ocular conditions examined in those studies. Researchers might have deliberately avoided studying ocular conditions that they might have expected to have made the online calibration of the eye tracker difficult, for instance, in individuals with nystagmus, strabismus, or abnormal anterior segments. This would most likely result in an overestimation of the actual success rate for individuals with vision impairment. In support, closer examination of the ocular conditions studied across all five paradigms shows that many studies focused largely on conditions that affect the macula or the optic nerve. From a total of 870 individuals with vision impairment addressed in this systematic review, 29.2% had a form of macular degeneration, and 24.8% had glaucoma. This observation is hardly surprising, given that these two conditions are among the most commonly occurring ocular conditions that lead to vision impairment.[74] However, of the estimated 2.2 billion individuals with vision impairment globally, only approximately 9% have age-related macular degeneration, and approximately 3% have glaucoma.[74] Apparently, there is an overrepresentation of individuals with macular degeneration and glaucoma among the studies using eye tracking in individuals with vision impairment. In contrast, other conditions are evidently poorly represented or even absent. This is particularly the case for individuals with an abnormal anterior segment (e.g., cataract, corneal opacity, aphakia, keratoconus), with none of the 870 participants included in this systematic review reportedly having any of these conditions (with cataract alone causing approximately 7% of worldwide vision impairment).[74] One possible explanation is that surgical treatment is well known to improve visual function in those conditions in developed countries. An alternative explanation could be that eye tracking is challenging in at least some of those conditions. Conditions that damage the peripheral retina are another so-far understudied set of conditions. Although 4% of participants in this review did have retinitis pigmentosa, none had diabetic retinopathy compared with it causing 7% of vision impairment globally.[74] It is possible that some of these ocular conditions have yet to be studied because of the challenges associated with tracking eye movements in those cases, or rather that the visual impairment caused by these conditions may not significantly affect eye movements.

A few points stand out when focusing on the distribution of the types of vision impairment investigated using each test paradigm. Studies of fixation stability and smooth pursuit focused exclusively on impairments that affected visual acuity (e.g., macular degeneration, amblyopia), whereas studies of saccades and free viewing mainly focused on vision impairments that affect peripheral vision (e.g., glaucoma, retinitis pigmentosa, hemianopia). In a sense, this division is logical, given that fixation stability and smooth pursuit rely on foveal vision, which is usually spared in glaucoma or hemianopia, whereas saccades to salient features are driven by peripheral vision. However, the relationship between performance on the different test paradigms remains unexplored, for example, whether unstable fixation in an age-related macular degeneration patient is associated with or indeed could explain prolonged saccade latencies in a saccade paradigm or prolonged fixation durations during free viewing.

Calibration of the eye tracker can be challenging in vision impairment, especially in individuals with macular degeneration. Eccentric fixation due to a central scotoma creates an offset in the gaze data, which posed problems for several eye trackers. In the study by Giacomelli et al.,[43] calibration had to be repeated several times until a good calibration could be obtained in individuals with macular degeneration using the Tobii Pro-2; Taylor et al.[54] faced a similar problem using the EyeLink II. Calibration procedures also had to be repeated with the EyeLink 1000 in glaucoma patients.[19] These repeated calibration procedures are time consuming; it was reported that it could take up to 25 minutes to be ready for data collection.[19] If the goal is to apply eye tracking in clinical practice, this preparation time needs to be minimized. One solution could be the use of a calibration-free eye tracker, such as the Pupil Labs Invisible from Pupil Labs GmbH. This eye tracker applies deep learning to process images of the eyes and scene to derive its point of gaze. However, it should be noted that the deep learning algorithms are trained on healthy eyes, which raises concerns about their accuracy in interpreting eye movements in the presence of impairment. Algorithms would need to be trained using impaired eyes to be suitable for testing individuals with vision impairment.

Individuals with vision impairment might, in some cases, compensate for their impairment by making more head rather than eye movements, and these head movements need to be accounted during eye tracking. Mobile eye trackers are not affected by head movements in the sense that data loss is not typically a threat. Remote (desk-mounted) eye trackers function optimally, though, when the head is located at the center of what is called the "headbox," which is determined by the participant's distance from the eye tracker and the angle of view of the eye tracker's camera. Therefore, excessive head movements can lead to data loss, as was reported by Thibaut et al.[55] In their study, 4 of 20 age-related macular degeneration patients had to be excluded from the analysis because more than 25% of their eye movement data were missing because of head movements. In their later study, 15 of 32 age-related macular degeneration patients had to be excluded for the same reason.[56] Explicitly instructing participants to limit head movements might reduce the amplitude of those movements. In severe cases, restraining the head to prioritize data quality over natural viewing conditions is an option. When assessing fixation stability or smooth pursuit, steady fixation on the target is required. It has been shown that fixation stability and smooth pursuit gain tend to be overestimated when the head is restrained.[21,62] When unconstrained, small eye movements are made to compensate for head movements, and this covariation can confound the analysis of fixation stability and smooth pursuit gain. In addition, it is important to note that different eye-tracking systems handle head movements differently. For instance, systems such as the EyeLink 1000 compensate for small head movements, as they measure gaze as eye position in space, not just eye-in-head position. On the other hand, head-mounted eye trackers incorporate the vestibular system's response to head movement in their output. This distinction means that the same subject behavior might be reported differently by different systems because of their measurement methodologies. Although restraining the head might help control certain confounding factors, it does, however, reduce the degree to which the testing represents the level of functional vision the patient has in daily life where gaze is determined via a combination of eye and head movements. If the goal of vision testing is to understand an individual's level of functional vision during activities of daily living, then the test paradigm should be designed to sample the natural behavior as best as possible. In that sense, the head should not be restrained. To evaluate the nature or extent of the vision impairment itself, it may be better to restrain the head.

Another important choice in test design is whether to test individuals with vision impairment monocularly or binocularly when testing their eye movements. Gestefeld et al.[19] compared the effect of monocular and binocular viewing on free-viewing behavior in glaucoma patients and demonstrated that monocular viewing was necessary to reveal abnormalities in glaucoma patients, particularly when the visual field defects were asymmetric. On the one hand, it is valuable to quantify the functional deficits in these patients. On the other hand, the results also indicate that the visual field loss would not have altered the free-viewing behavior of the patients when viewing naturally under binocular conditions. Results from tests of smooth pursuit have also shown that performance is dependent on when viewing binocularly, and therefore, visual function when assessed binocularly might yield the most valuable information for assessing functional vision. Taken together, the results highlight the need to consider the role of the test when choosing whether to test binocularly or monocularly in individuals with vision impairment.

An important issue when interpreting eye-tracking data is that one should have some estimate of the accuracy and precision of the data that are provided.[75] For people with normal vision, such information can be found within the documentation accompanying the equipment and in publications for most commonly used eye trackers.[76–78] For instance, the EyeLink manual itself reports an accuracy of 0.5° in optimal conditions, but it would be naive to assume that this accuracy would hold for many individuals with vision impairment. None of the studies in our sample assessed data quality, which could be a serious problem when interpreting the results. This is even more significant when using manufacturer software supplied for the analysis. Comprehensive examination of the raw data itself is also necessary. Note that data quality is determined not only by how well the eye tracker can follow the eyes but also by how reliably it can be calibrated.

Some eye trackers have a temporal resolution of up to 1000 Hz, but some (older) eye trackers, or newer mobile eye trackers, can be limited to a sample rate of approximately 50 to 60 Hz or sometimes have a variable frame rate. The lower sample rates might not be sufficient for the accurate analysis of saccadic parameters (e.g., peak velocity).[27,35,49] This limitation has not been reported by articles when using an eye tracker with a sample rate of 120 Hz and higher and is therefore recommended as the minimal sample rate for the reliable analysis of saccadic dynamics.

The last point concerns the inclusion in studies of a representative control group. Control groups for age-related vision impairments such as age-related macular degeneration and glaucoma require the recruitment of older adults with good vision who are free from ocular disorders and cognitive deficits. Difficulties recruiting appropriate control subjects have been reported, sometimes resulting in noticeable differences in the age of the impaired and control participants (e.g., 17- to 28-year-old control participants vs. 25- to 67-year-old patients[51]) or a wide range of ages in the control group (e.g., 16 to 74 years old[39]). How confounding factors such as cognitive skill, visual function (acuity and contrast sensitivity), sex, culture, and health status might affect the comparison of eye movements between control groups and groups with vision impairment remains unknown.

Limitations

Although our systematic review aimed to explore eye-tracking studies involving individuals with vision impairment, certain limitations merit consideration. One notable limitation is the absence of paradigms that examine vergence in participants with impairment. Vergence is a fundamental aspect of binocular vision and holds relevance in the field of eye care. However, vergence was not tested in the studies included in our review because gaze was tested using two-dimensional screen-based tasks rather than tasks in depth. The increasing adoption of mobile eye tracking may, in the future, encourage the development of paradigms that offer the opportunity to test vergence eye movements.

Although in this review we focused solely on the test paradigms used in studies using video-based eye tracking, it is possible that other paradigms do exist that have been examined using technologies other than video-based eye tracking. For instance, a variety of test paradigms have been used to characterize the velocity and amplitudes of saccades using electrooculography, a limbus tracking system, and a scleral search coil.[79–82] These techniques have been used to characterize, for instance, slow and hypometric saccades, serving as clinical indicators of neural mechanisms controlling eye movements in disease[83,84] or as a direct effect of vision impairment.[85,86] Similarly, measures of smooth pursuit such as the pursuit gain have been reliably obtained using other systems.[81,87] The clinical significance of these measures is well established.[84,87–89] These findings can serve as a reference for researchers and clinicians as a source of additional paradigms that could be used (or even improved) using modern video-based eye-tracking technology.

CONCLUSIONS

This systematic review reveals a growing and promising field of research, with the increasingly common use of tests of fixation stability, smooth pursuit, saccades, free viewing, and visual search. This review highlights an overrepresentation of studies in conditions that affect the optic nerve or macula and an underrepresentation of conditions that affect the anterior segment or peripheral retina. The results show that usable data can be collected from 96.5% of participants, and even though this likely reflects the selectiveness of the ocular conditions examined to date, this offers promise that eye tracking can be used to assess the visual function of a considerable proportion of those with vision impairment.

ARTICLE INFORMATION

Supplemental Digital Content: Appendix Table A1, available at http://links.lww.com/OPX/A697: Full search syntax for the PubMed database for replication purposes.

Appendix Table A2, available at http://links.lww.com/OPX/A697: Table containing the full search syntax and results for the Embase.com database for replication purposes.

Appendix Table A3, available at http://links.lww.com/OPX/A697: Table containing the full search syntax and results for the Web of Science database for replication purposes.

Appendix Table A4, available at http://links.lww.com/OPX/A697: Study characteristics of the studies included for qualitative synthesis. The table consists of information on the authors, patient information, and eye-tracker characteristics.

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REFERENCES

1. Mann DL, Spratford W, Abernethy B. The Head Tracks and Gaze Predicts: How the World's Best Batters Hit a Ball. PLoS One 2013;8:e58289.

2. Castaneda L, Sidhu MK, Azose JJ, et al. Game Play Differences by Expertise Level in Dota 2, a Complex Multiplayer Video Game. Int J Gaming Comput Mediat Simul 2016;8:1–24.

3. Gil AM, Birdi S, Kishibe T, et al. Eye Tracking Use in Surgical Research: A Systematic Review. J Surg Res 2022;279:774–87.

4. Lefrançois O, Matton N, Causse M. Improving Airline Pilots' Visual Scanning and Manual Flight Performance through Training on Skilled Eye Gaze Strategies. Safety 2021;7(4):70.

5. Diefendorf AR, Dodge R. An Experimental Study of the Ocular Reactions of the Insane from Photographic Records. Brain 1908;31:451–89.

6. Faiola E, Meyhofer I, Ettinger U. Mechanisms of Smooth Pursuit Eye Movements in Schizotypy. Cortex 2020;125:190–202.

7. Morita K, Miura K, Kasai K, et al. Eye Movement Characteristics in Schizophrenia: A Recent Update with Clinical Implications. Neuropsychopharmacol Rep 2020;40:2–9.

8. Harezlak K, Kasprowski P. Application of Eye Tracking in Medicine: A Survey, Research Issues and Challenges. Comput Med Imaging Graph 2018;65:176–90.

9. Hunt AW, Mah K, Reed N, et al. Oculomotor-based Vision Assessment in Mild Traumatic Brain Injury: A Systematic Review. J Head Trauma Rehabil 2016;31:252–61.

10. Papagiannopoulou EA, Chitty KM, Hermens DF, et al. A Systematic Review and Meta-analysis of Eye-tracking Studies in Children with Autism Spectrum Disorders. Soc Neurosci 2014;9:610–32.

11. Tao L, Wang Q, Liu D, et al. Eye Tracking Metrics to Screen and Assess Cognitive Impairment in Patients with Neurological Disorders. Neurol Sci 2020;41:1697–704.

12. Dell'Osso LF, Daroff RB. Congenital Nystagmus Waveforms and Foveation Strategy. Doc Ophthalmol 1975;39:155–82.

13. Ballae Ganeshrao S, Jaleel A, Madicharla S, et al. Comparison of Saccadic Eye Movements among the High-tension Glaucoma, Primary Angle-closure Glaucoma, and Normal-tension Glaucoma. J Glaucoma 2021;30:e76–82.

14. Lamirel C, Milea D, Cochereau I, et al. Impaired Saccadic Eye Movement in Primary Open-angle Glaucoma. J Glaucoma 2014;23:23–32.

15. Najjar RP, Sharma S, Drouet M, et al. Disrupted Eye Movements in Preperimetric Primary Open-angle Glaucoma. Invest Ophthalmol Vis Sci 2017;58:2430–7.

16. White JM, Bedell HE. The Oculomotor Reference in Humans with Bilateral Macular Disease. Invest Opthalmol Vis Sci 1990;31:1149–61.

17. Whittaker SG, Dudd J, Cummings RW. Eccentric Fixation with Macular Scotoma. Invest Ophthalmol Vis Sci 1988;29:268–78.

18. Dunn MJ, Harris CM, Ennis FA, et al. An Automated Segmentation Approach to Calibrating Infantile Nystagmus Waveforms. Behav Res Methods 2019;51:2074–84.

19. Gestefeld B, Marsman JB, Cornelissen FW. How Free-viewing Eye Movements Can be Used to Detect the Presence of Visual Field Defects in Glaucoma Patients. Front Med (Lausanne) 2021;8:689910.

20. Murray J, Gupta P, Dulaney C, et al. Effect of Viewing Conditions on Fixation Eye Movements and Eye Alignment in Amblyopia. Invest Ophthalmol Vis Sci 2022;63:33.

21. Shanidze NM, Velisar A. Eye, Head, and Gaze Contributions to Smooth Pursuit in Macular Degeneration. J Neurophysiol 2020;124:134–44.

22. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. BMJ 2021;372:n71.

23. Land MF. Eye Movements and the Control of Actions in Everyday Life. Prog Retin Eye Res 2006;25:296–324.

24. Vandenbroucke JP, von Elm E, Altman DG, et al. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): Explanation and Elaboration. Int J Surg 2014;12:1500–24.

25. Tarita-Nistor L, Brent MH, Steinbach MJ, et al. Fixation Stability during Binocular Viewing in Patients with Age-related Macular Degeneration. Invest Ophthalmol Vis Sci 2011;52:1887–93.

26. Shaikh AG, Otero-Millan J, Kumar P, et al. Abnormal Fixational Eye Movements in Amblyopia. PLoS One 2016;11:e0149953.

27. González EG, Teichman J, Lillakas L, et al. Fixation Stability Using Radial Gratings in Patients with Age-related Macular Degeneration. Can J Ophthalmol 2006;41:333–9.

28. Macedo AF, Crossland MD, Rubin GS. Investigating Unstable Fixation in Patients with Macular Disease. Invest Ophthalmol Vis Sci 2011;52:1275–80.

29. Bellmann C, Feely M, Crossland MD, et al. Fixation Stability Using Central and Pericentral Fixation Targets in Patients with Age-related Macular Degeneration. Ophthalmology 2004;111:2265–70.

30. Bethlehem RA, Dumoulin SO, Dalmaijer ES, et al. Decreased Fixation Stability of the Preferred Retinal Location in Juvenile Macular Degeneration. PLoS One 2014;9:e100171.

31. Crossland MD, Culham LE, Rubin GS. Fixation Stability and Reading Speed in Patients with Newly Developed Macular Disease. Ophthalmic Physiol Opt 2004;24:327–33.

32. Tarita-Nistor L, Brent MH, Steinbach MJ, et al. Fixation Patterns in Maculopathy: From Binocular to Monocular Viewing. Optom Vis Sci 2012;89:277–87.

33. Tarita-Nistor L, González EG, Brin T, et al. Fixation Stability and Viewing Distance in Patients with AMD. Optom Vis Sci 2017;94:239–45.

34. Crossland MD, Sims M, Galbraith RF, et al. Evaluation of a New Quantitative Technique to Assess the Number and Extent of Preferred Retinal Loci in Macular Disease. Vision Res 2004;44:1537–46.

35. Macedo AF, Nascimento SM, Gomes AO, et al. Fixation in Patients with Juvenile Macular Disease. Optom Vis Sci 2007;84:852–8.

36. Ghasia FF, Otero-Millan J, Shaikh AG. Abnormal Fixational Eye Movements in Strabismus. Br J Ophthalmol 2018;102:253–9.

37. Kelly KR, Cheng-Patel CS, Jost RM, et al. Fixation Instability during Binocular Viewing in Anisometropic and Strabismic Children. Exp Eye Res 2019;183:29–37.

38. González EG, Wong AM, Niechwiej-Szwedo E, et al. Eye Position Stability in Amblyopia and in Normal Binocular Vision. Invest Ophthalmol Vis Sci 2012;53:5386–94.

39. González EG, Tarita-Nistor L, Mandelcorn E, et al. Mechanisms of Image Stabilization in Central Vision Loss: Smooth Pursuit. Optom Vis Sci 2018;95:60–9.

40. Rashbass C. The Relationship between Saccadic and Smooth Tracking Eye Movements. J Physiol 1961;159: 326–38.

41. Shanidze N, Heinen S, Verghese P. Monocular and Binocular Smooth Pursuit in Central Field Loss. Vision Res 2017;141:181–90.

42. Raashid RA, Liu IZ, Blakeman A, et al. The Initiation of Smooth Pursuit Is Delayed in Anisometropic Amblyopia. Invest Ophthalmol Vis Sci 2016;57:1757–64.

43. Giacomelli G, Farini A, Baldini I, et al. Saccadic Movements Assessment in Eccentric Fixation: A Study in Patients with Stargardt Disease. Eur J Ophthalmol 2021;31:2556–62.

44. Fayel A, Chokron S, Cavezian C, et al. Characteristics of Contralesional and Ipsilesional Saccades in Hemianopic Patients. Exp Brain Res 2014;232:903–17.

45. Raashid RA, Wong AM, Chandrakumar M, et al. Short-term Saccadic Adaptation in Patients with Anisometropic Amblyopia. Invest Ophthalmol Vis Sci 2013;54:6701–11.

46. Niechwiej-Szwedo E, Goltz HC, Chandrakumar M, et al. Effects of Anisometropic Amblyopia on Visuomotor Behavior, I: Saccadic Eye Movements. Invest Ophthalmol Vis Sci 2010;51:6348–54.

47. Niechwiej-Szwedo E, Chandrakumar M, Goltz HC, et al. Effects of Strabismic Amblyopia and Strabismus without Amblyopia on Visuomotor Behavior, I: Saccadic Eye Movements. Invest Ophthalmol Vis Sci 2012;53: 7458–68.

48. Smith ND, Crabb DP, Glen FC, et al. Eye Movements in Patients with Glaucoma when Viewing Images of Everyday Scenes. Seeing Perceiving 2012;25:471–92.

49. Pambakian AL, Wooding DS, Patel N, et al. Scanning the Visual World: A Study of Patients with Homonymous Hemianopia. J Neurol Neurosurg Psychiatry 2000;69:751–9.

50. Asfaw DS, Jones PR, Monter VM, et al. Does Glaucoma Alter Eye Movements when Viewing Images of Natural Scenes? A Between-eye Study. Invest Ophthalmol Vis Sci 2018;59:3189–98.

51. Gameiro RR, Junemann K, Herbik A, et al. Natural Visual Behavior in Individuals with Peripheral Visual-field Loss. J Vis 2018;18:10.

52. Titchener SA, Ayton LN, Abbott CJ, et al. Head and Gaze Behavior in Retinitis Pigmentosa. Invest Ophthalmol Vis Sci 2019;60:2263.

53. Chen D, Otero-Millan J, Kumar P, et al. Visual Search in Amblyopia: Abnormal Fixational Eye Movements and Suboptimal Sampling Strategies. Invest Ophthalmol Vis Sci 2018;59:4506–17.

54. Taylor DJ, Smith ND, Crabb DP. Searching for Objects in Everyday Scenes: Measuring Performance in People with Dry Age-related Macular Degeneration. Invest Ophthalmol Vis Sci 2017;58:1887–92.

55. Thibaut M, Delerue C, Boucart M, et al. Visual Exploration of Objects and Scenes in Patients with Age-related Macular Degeneration. J Fr Ophthalmol 2016;39:82–9.

56. Thibaut M, Boucart M, Tran TH. Object Search in Neovascular Age-related Macular Degeneration: The Crowding Effect. Clin Exp Optom 2020;103:648–55.

57. Coeckelbergh TF, Cornelissen FW, Brouwer WH, et al. The Effect of Visual Field Defects on Eye Movements and Practical Fitness to Drive. Vision Res 2002; 42:669–77.

58. Van der Stigchel S, Bethlehem RA, Klein BP, et al. Macular Degeneration Affects Eye Movement Behavior during Visual Search. Front Psychol 2013;4:579.

59. Smith ND, Glen FC, Crabb DP. Eye Movements during Visual Search in Patients with Glaucoma. BMC Ophthalmol 2012;12:45.

60. Wiecek E, Pasquale LR, Fiser J, et al. Effects of Peripheral Visual Field Loss on Eye Movements during Visual Search. Front Psychol 2012;3:472.

61. Yarbus A. Eye Movements and Vision. New York, NY: Plenum Press; 1967.

62. Crossland MD, Rubin GS. The Use of an Infrared Eyetracker to Measure Fixation Stability. Optom Vis Sci 2002;79:735–9.

63. Pirdankar OH, Das VE. Influence of Target Parameters on Fixation Stability in Normal and Strabismic Monkeys. Invest Ophthalmol Vis Sci 2016;57:1087–95.

64. Thaler L, Schutz AC, Goodale MA, et al. What Is the Best Fixation Target? The Effect of Target Shape on Stability of Fixational Eye Movements. Vision Res 2013;76:31–42.

65. Rizzo JR, Beheshti M, Dai W, et al. Eye Movement Recordings: Practical Applications in Neurology. Semin Neurol 2019;39:775–84.

66. Mazumdar D, Pel JJ, Panday M, et al. Comparison of Saccadic Reaction Time between Normal and Glaucoma Using an Eye Movement Perimeter. Indian J Ophthalmol 2014;62:55–9.

67. Mazumdar D, Pel JJ, Kadavath Meethal NS, et al. Visual Field Plots: A Comparison Study between Standard Automated Perimetry and Eye Movement Perimetry. J Glaucoma 2020;29:351–61.

68. Cifu DX, Wares JR, Hoke KW, et al. Differential Eye Movements in Mild Traumatic Brain Injury versus Normal Controls. J Head Trauma Rehabil 2015;30:21–8.

69. Maruta J, Suh M, Niogi SN, et al. Visual Tracking Synchronization as a Metric for Concussion Screening. J Head Trauma Rehab 2010;25:293–305.

70. Williams IM, Ponsford JL, Gibson KL, et al. Cerebral Control of Saccades and Neuropsychological Test Results after Head Injury. J Clin Neurosci 1997;4: 186–96.

71. Acik A, Onat S, Schumann F, et al. Effects of Luminance Contrast and Its Modifications on Fixation Behavior during Free Viewing of Images from Different Categories. Vision Res 2009;49:1541–53.

72. Harding G, Bloj M. Real and Predicted Influence of Image Manipulations on Eye Movements during Scene Recognition. J Vis 2010;10:8.1–17.

73. Smith ND, Crabb DP, Garway-Heath DF. An Exploratory Study of Visual Search Performance in Glaucoma. Ophthalmic Physiol Opt 2011;31:225–32.

74. World Health Organization. World Report on Vision; 2019. Available at: https://www.who.int/docs/default-source/documents/publications/world-vision-report-accessible.pdf. Accessed November 17, 2023.

75. Holmqvist K, Orbom SL, Hooge IT, et al. Eye Tracking: Empirical Foundations for a Minimal Reporting Guideline. Behav Res Methods 2023;55:364–416.

76. Ehinger BV, Gross K, Ibs I, et al. A New Comprehensive Eye-tracking Test Battery Concurrently Evaluating the Pupil Labs Glasses and the EyeLink 1000. PeerJ 2019;7:7086.

77. Funke G, Greenlee E, Carter M, et al. Which Eye Tracker Is Right for Your Research? Performance Evaluation of Several Cost Variant Eye Trackers. Proc Hum Factors Ergon Soc Annu Meet 2016;60:1240–4.

78. Tonsen M, Baumann CK, Dierkes K. A High-Level Description and Performance Evaluation of Pupil Invisible. arXiv 2020; arXiv:2009.00508.

79. Wilson SJ, Glue P, Ball D, et al. Saccadic Eye Movement Parameters in Normal Subjects. Electroencephalogr Clin Neurophysiol 1993;86:69–74.

80. Yee RD, Schiller VL, Lim V, et al. Velocities of Vertical Saccades with Different Eye Movement Recording Methods. Invest Ophthalmol Vis Sci 1985;26:938–44.

81. Collewijn H, Tamminga EP. Human Smooth and Saccadic Eye Movements during Voluntary Pursuit of Different Target Motions on Different Backgrounds. J Physiol 1984;351:217–50.

82. Collewijn H, Erkelens CJ, Steinman RM. Voluntary Binocular Gaze-shifts in the Plane of Regard: Dynamics of Version and Vergence. Vision Res 1995;35:3335–58.

83. Bird AC, Leech J. Internuclear Ophthalmoplegia: An Electro-oculographic Study of Peak Angular Saccadic Velocities. Br J Ophthalmol 1976;60:645–51.

84. Barton JJ, Sharpe JA. Smooth Pursuit and Saccades to Moving Targets in Blind Hemifields: A Comparison of Medial Occipital, Lateral Occipital and Optic Radiation Lesions. Brain 1997;120:681–99.

85. Whittaker SG, Cummings RW, Swieson LR. Saccade Control without a Fovea. Vision Res 1991;31:2209–18.

86. Maxwell GF, Lemij HG, Collewijn H. Conjugacy of Saccades in Deep Amblyopia. Invest Ophthalmol Vis Sci 1995;36:2514–22.

87. Versino M, Beltrami G, Zambarbieri D, et al. A Clinically Oriented Approach to Smooth Pursuit Eye Movement Quantitative Evaluation. Acta Neurol Scand 1993; 88:273–8.

88. Levin S, Luebke A, Zee DS, et al. Smooth Pursuit Eye Movements in Schizophrenics: Quantitative Measurements with the Search-coil Technique. J Psychiatr Res 1988;22:195–206.

89. Bittencourt M, Gresty MA, Richens A. Quantitative Assessment of Smooth-pursuit Eye Movements in Healthy and Epileptic Subjects. J Neurol Neurosurg Psychiatry 1980;43:1119–24.