OPEYE

Survey on gaze estimation in the context of visual impairments.

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This project has been funded with support from the European Commission.

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Abstract

The gaze of a person, used as a mean of input for a computer offers many potential benefits. This is especially true with respect to people with special needs, such as visual impairments.

This survey documents the research for a real-life use case of a gaze-based application. Precisely, the gaze-based magnification of computer screen contents for people with reduced visual acuity. Techniques, impacts of visual impairments and previous work in all the relevant fields are discussed.

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Introduction

Controlling a computer is usually done using a keyboard and a mouse. Other means of intuitive input methods would be to control the computer either by audio or video input. Voice command-based input is becoming more and more popular respectively feasible [1]. It has recently peaked in commercial personal assistant applications for various platforms (e.g. Siri, OK Google, Cortana, Alexa, ...). On the other hand, video-based input is not yet as common. Computational capabilities and mathematical complexities have up to now restricted progress in this field without the use of additional hardware [2].

The progress in hardware development and machine learning though lead to huge improvements of possibilities. While for long it appeared that OCR and simple object or feature detection were the pinnacle of what seemed possible with visual processing using a computer, nowadays face & object detection are using special trained convolutional neural networks to describe pictures in social networks or on mobile platforms [3]. Detecting a face in an image is no longer considered a very complex task. The same is true for detecting the center of a pupil within a picture frame. Even without the use of modern neural networks it is possible to perform the computations required to estimate the gaze point on a screen of an observer, but these approaches are prone to many external factors [4] and lack in speed as well as in precision. On the one hand we have eye localisation and tracking which is the detection of the existence of eyes and track them from frame to frame. On the other hand, we have gaze estimation which, as the name suggests, is the estimation where the person is looking. In this survey we will first describe eye tracking (ET) in more detail before elaborating more on gaze estimation (GE). Then we will discuss the different visual impairments and how they might impact a gaze estimation system. Finally, we will describe what screen magnification is used for and how gaze-based control can improve the user experience. [5]

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Evolution

Early work in the field aimed to understand the eye's motion in the context of reading. Nothing was known on saccades and other eye behaviours. It was widely assumed that while reading, the eyes move along a linear path reading character by character, word by word and sentence by sentence.

The first approaches to systematically analyze this, tried to evaluate the eye's motion by direct observation. In order to achieve more precise data, simple contact lenses connected to an aluminium pointer that moved in accordance to the eye, allowed to verify the eye's motion in greater detail. [6] It was discovered that in the context of reading, the eye follows a more complex path than initially assumed. This was followed by a noninvasive approach that tried to illuminate the eye with a beam of light and film it systematically.

Beginning with the 1950's, more complex machines were built to record eye motions of a subject while the head was fixed. This allowed a more precise interpretation of the users view. [7] A whole theory on how the user's gaze is centred around his point of interest was developed around this time. In the 70's, a lot more research on the field has been done, mostly aiming to improve the understanding of the reading process. [8]

With the 1980's, and the abundance of PCs available to the public, the idea that eye-tracking could be used for human machine interaction became popular. Computers allowed for the first time to use a rough form of eye-tracking in real-time to help disabled users. [9]

In more recent years a lot of effort went into the interpretation of a user's eye motion when analyzing their gaze on websites, publicities or user interfaces to understand what attracts attention and how it could be optimized. For this, very precise systems are required and commercial setups with multiple cameras, adequate lighting and software can be purchased.

Nowadays we differentiate between 3 approaches to measure the eye's rotation. With eye-attached systems, a contact lens that can actively be located on the eye by either reflecting light or by changing a magnetic field can be measured. With the electric potential measurement an electric field generated between the eye's cornea and retina is captured with electrodes placed around the eye balls. This field can be mapped to an eye orientation. The most common approach though is to film the eye using a digital camera and perform processing on the image data. This is referred to as video-based approach. As described above, the aim is to analyze an image and understand how the eyes can be mapped to screen space coordinates. Until recently, model and feature based approaches dominated the research, but machine learning based approaches start to become more relevant. Machine learning became possible due to

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the availability of massive computational power and great progress in learning approaches. In this context, a neural network is taught to understand a person's gaze and map it to screen space.

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Basics

Gaze-estimation is the action of guessing a point on a screen that is looked at by an observer. It is not to be confused with eye-tracking, described below, which is merely the task of locating an observer's eye position in a 2D picture or video frame [4]. Hence eye-tracking is likely to be a subtask of what is required to compute a gaze point, but not a necessity. Especially using convolutional neural networks, it is possible that the eye-tracking is done implicitly [10].

In plain English, gaze-estimation should provide precise 2D screen coordinates that represent the focal point of a user's gaze to a computer program at any time. Video based approaches realize this, by analysing a video frame, isolating an observer's eye properties and transforming them into screen space coordinates.

When talking about video-based approaches we differentiate primarily between model and feature-based approaches. Model-based approaches try to match an image based on a model of an eye to an input picture. Thus, knowing the variables to generate the model in a certain state, the gaze point can be estimated or computed respectively. Feature-based approaches try to estimate the gaze points based on clearly distinguishable parts or features of the eye. Frequently the pupil center or the limbus (the boundary between iris and sclera) serve as such features. An ellipse is fitted to precisely match the pupil and hence, the eye state can be deduced. The camera position with respect to the eye is an important factor that must be considered in this computation. Remote gaze-estimation systems are filming an observer from a fixed location such as a webcam mounted on a monitor. In this case, an eye-tracking method must first be applied to isolate the eyes before the gaze can be interpreted. Alternatively, you can mount a camera close to the observer's eye or even eyes and thus sacrifice comfort for quality.

To do gaze estimation, we need to find the eyes of the user. The precise identification of the center of the pupil and the measuring of its movements is what we call eye-tracking. There are different techniques how we can achieve this. For some time, it was not possible to track the eye without special hardware, such as a chin-rest, but nowadays this is no longer required. Although it is less intrusive not using a chin-rest, it suffers from a reduced accuracy. [6] Head mounted cameras don't need to interpret the observer's head position and can thus achieve better performance and higher quality. The image contains only the relevant part and not eye isolation is required because the position is known.

In general, most current approaches are very prone to external factors. In order to achieve robustness, these issues must be dealt with. The major influences are:

- Lighting
- Image quality

- Head/Camera position & motion
- Glasses
- Processing power
- Training data sets
- Calibration
- Visual impairments

Lighting affects both, the discovery of features in the image as well as potential glints on the eye that can easily be misinterpreted. Low contrast due to a bad lighting situation might lead to the inability to pinpoint the center of the pupil. Glints, from corneal reflections must be eliminated or ignored to achieve good results. Other techniques provoke glints to use them for the gaze estimation computation (Dual Purkinje) [11]. Sometimes an initial step applies a histogram equalization to the images to reduce the dependence on varying lighting situations.

Low image quality, in terms of resolution, sharpness and contrast, will reduce the precision. This is because these aspects lead to an actual reduction of input data in qualitative and quantitative terms, some of which can be reconstructed, and some can't. The center of a pupil can be found in a pixelated, blurry picture of the eye with the help of a fitting algorithm, but it is easier and usually more precise if the quality of the input image is high. Model based fitting of ellipses to a pupil works best with the least aliased images.

The position of the user with respect to the camera is of utter importance as it defines the way the detected pupil state is mapped to screen space coordinates. In many systems, the head is kept on a chin-rest. Knowing the precise position of the eyeball relative to the screen allows to statically configure a geometric mapping and to achieve good results. The alternative approach requires an additional step, that is, it must discover the face first and interpret its appearance to deduce a geometric state and precisely discover the eyeballs. This way is more flexible for the user but comes at the cost of potentially less precision. This case would allow creation of applications with eye tracking on mobile systems. But having a camera and face that might move relative to each other with standard hardware will lead to motion blur. This obviously further complicates the situation and must be accounted for.

Processing images is frequently a very CPU and memory consuming process. The higher the resolution of the input image, the better the results of the gaze-estimation. Doubling the resolution squares the memory bandwidth and CPU iteration time of the pixels of the images. Parallel computing on multiple cores improves the ability to deal with that much data, but complicates development to a certain extend. Image processing requires repetition of the same operations on the different pixels. Hence it is a perfect case for the use of SIMD (Single Input Multiple Data) architecture-based processors. Modern graphics processing units (GPUs) implement this type of

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architecture. In recent years the power of GPUs has been made accessible for computational use other than 3D rendering by software libraries such as CUDA or OpenCL.

The machine learning based approaches require large and versatile training data sets. These sets are libraries of labeled images showing users that gaze at points on a screen. Output data based on a known input is used to train a neural network to understand a certain scenario. In our case the neural network will learn how to interpret a picture of a user looking at the screen and then return the resulting screen coordinates. Apart from the machine learning context, labeled data can be used to verify any approach. Taking the distance between a point measured when feeding the algorithm with a labeled sample and the actual point at which the user looked at, can serve as quality metric. There are some sets available for public use, but none of them are labeled for users with visual impairments.

The whole approach is very prone to changing variables. If any parameter changes, including those of eye-tracking, the computation must be re-calibrated. Moving the head, a bit or changing the webcam's position will lead to different outcomes. Optimal solutions will automatically account for this, moving the webcam or head would not affect the quality of gaze estimation results, but there is no such optimal solution yet. A realistic approach is to at least assume a static webcam position with respect to the screen and interpret the webcam image to understand the distance of the viewer.

Besides all these aspects there are obvious additional potential sources of problem like wearing glasses, having a glass eye or a missing eye. The effects of visual impairments on gaze estimation will be elaborated in the section "Visual impairments"

Eye-Tracking

Human faces share common feature, such as high cheeks and nose bridge which appear brighter in colour than the eye region. In combination with the location and size, these features are sought in an image. Such features a called Haar-features. An integral image representation is formed which creates rectangular feature regions. An algorithm is then applied to train classifiers to detect the objects. This method is called the Viola-Jones object detection framework. [12] To get better results, 2 of Viola Jones detectors are used in [13], one for the profile of the face, the other for the frontal view.The Shi-Tomasi detector [14] is used to detect corner points. These are clustered using K-Means [15] method before determining eye candidate regions. At last, the localisation is achieved by matching these regions with an eye template. [13]

The methods used to do eye detection can be classified into five categories. Shape-based approaches, feature-based shape methods, appearance-based methods, hybrid models and other models that do not fit under any of the other categories.

Simple elliptical Shape models, which belong to the first category, consist of voting-based and model-based methods. Voting-based methods select features that support a given hypothesis through a voting process. Model fitting fit selected features, such as en ellipse, to the model. Complex Shape models which also fall under the shape-based approach and allow more detailed modelling of the eye shape.

Feature-based shape methods include local features by intensity, local features by filter responses and pupil detection. Local features by intensity include the localisation of the eye by detecting gray-level differences such as edges, lines and their orientation, lengths and scale.

Local feature by Filter Responses need a definition of filters. Based on the quality of these, features are extracted from an image. Using different methods, edges of the eye sclera and eye corner candidates are detected. After irrelevant eye corner candidates are eliminated after post processing, a voting method is used to locate the edge of the iris. A u-shaped annular region is determined as the iris, and en annulus center receiving the most votes is selected as the iris center.

Haar feature-based classifiers [16] is an effective approach to identify objects. It uses machine learning cascading a large amount of positive and negative images. OpenCV, an open-source eye tracker, uses this approach. A large amount of positive images, in this case images containing faces, are used in addition to negative images, images without faces, are used to train the classifier.

Looking at the eye closely, the pupil is a reliable feature for eye detection. Therefore with pupil detection the iris and pupil can be detected as their surroundings are lighter in colour. All of these methods however cannot

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model eyes when they are closed but generally report good robustness during illumination changes.

Appearance-based methods detect and track eyes directly, based on the photometric appearance. They are also called image template or holistic methods. In image template based, the spatial and tensity information of each pixel are preserved in contrary to holistic approaches where the spatial information is ignored. Problems occur with scale and rotation, especially with single-template models which are prone to head pose and eye movements within the same person. Holistic approaches use statistical techniques to analyse the intensity distribution of the object. This approach uses a large amount of training data as the test image is compared with the stored prototypes.

Hybrid models combine the different advantages of the models in order to overcome the problems of these. In combining shape and appearance allow to explicitly model the individual part variances while implicitly modeling the appearance.

Some approaches use IR lighting to avoid glints completely and achieve constant illumination of the pupil. If the IR light source is located perpendicular to the camera sensor's normal, the pupil appears brighter than the rest of the eye due to reflection [17]. IR lighting however must be used in an indoor setting as the outdoor ambient light contains to much IR parts for the technique to work. Also IR might harm a person's eye if not used with the adequate precaution. [4]

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Gaze Estimation

The knowledge of where precisely a user is gazing on a screen allows for many interesting applications. The possibilities span from analyzing the perception of a user interface over to the control of video games solely with the eyes [18]. A major advantage of gaze estimation is that it can help people with limited coordinative and motor skills to use their eyes as input for the computer.

In an analogous approach one could thus use the computer to base medical diagnostics for people with visual impairments on this input. Our goal is to improve the interaction with the computer of persons with limited visual acuity.

Many ways to realize a well performing gaze estimation have been explored over the past decades [4]. Some are based on sensors measuring muscle tension [7] others use video based input. Most successful systems rely on either special hardware and/or a very robust setting. The precision and robustness of the systems are correlated to these external constraints. In the recent history notable improvements were made, better cameras, machine learning and computational power appear to allow for more user friendly and open systems. Although a vast amount of scientific research on gaze-tracking was published, hardly any mention the use of such systems with visual impairments.

Most of the products which use Gaze Tracking rely on previous calibration of the system. The calibration consists in some marks that are being shown on the screen and the software correlates those known coordinates (generally at the corners of the screen and in between those locations in a 3x3 matrix) with the pupils' locations. Logically, the more points on the screen, the more precise is going to be the gaze tracker, but the more time consuming the calibration process is. The correlation between eye-coordinates and screen marks is expressed mathematically as a convolutional matrix after the calibration, which is further used to transform the pupil coordinates in the video stream into screen coordinates so we can assume where the user is looking at by interpolating, in real time.

The main problem of this methodology is that, if head or camera location varies, a recalibration of the system is needed, because the local coordinates of the pupils inside the video frame are distinct from the first ones. Our approach is to try to make those coordinates relative to the head and therefore more robust to head or camera movements. Addinitionaly a head tracker is therefore needed. In despite of that solution, there could arise some problems if there is not enough contrast between the head and the background. Hair styling, which can change during the experimentation, or head rotations, which will lead to changes in the relative proportions of the head and the correlation to the eyes, need also be taken into consideration.

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Traditionally, in optometrics and ophthalmologic sciences, the solution is to add a fixed chin rest to the experiment, so users can lie on that structure, keeping the chin on the support and their forehead in contact with an upper solid band, and that make the eyes' position still and easier to track. We are also considering this option if the results are too unpredictable.

In our context

The aim is to provide a gaze driven magnification of portions of the screen in order to help people with low visual acuity. Access to a computer gives a person having a visual impairment a wider range of possibilities in personal and professional life. So far a lot of research is found on eye tracking and gaze estimation, but not many take a visual impairment into consideration. There are a lot of different visual impairments that are discussed in more detail at a later point in this survey. All these different eye conditions have to be taken into consideration when developing a gaze tracker for people having a visual impairment. For example, for a person with a strabism, the proper eye needs to be filtered in order ro the gaze estimation to work. Although there are sources that suggest that gaze estimation is not yet a solvable problem [44], we try to tackle the problem and use a convolutional neural network to get the results.

Methodology

Given the different techniques discussed earlier, HAAR cascades seem to be a reliable and accessible approach to isolate facial landmarks. OpenCV, a widely used open source library allows to do just this. After having isolated the eyes, the best suited eye is then furthermore isolated and a deep neural network is taught to map the input eye-image towards screen-space coordinates. In addition corneal reflection might occur and cause errors in centre estimation as well as locating pupil and iris boundaries. Algorithms discussed in [17] will in such a case be applied.

While machine learning approaches in the context of gaze-estimation do already exist [19] and are even available under open source licenses, the precision does not yet meet our requirements. Convolutional neural networks can help understand the images and estimate the gaze of the user.

The idea is to teach many neurons how to interpret the input image data and result in the screen space coordinates. A deep neural network, that is one with many layers of parallel neurons, allows to understand even the most complex data. The accuracy of them is strictly dependent on how big the neural network is, what computational power is available, how much time can be spend on training and the amount & quality of labeled training data.

However, none of these techniques yet take a visual impairment into consideration. Depending on the impairment, the eye tracking might not work as the features are not available. In addition to a dataset containing images of users without a visual impairment, we create a dataset with users having a visual impairment. To this end, a capture tool has been developed to record data. Users have to look at different points on the screen in order to map the gaze to the coordinates on the screen. The neural network will also be taught using these images in order to be able to cope with the different visual impairments. An algorithm will have to be implemented as the best suited eye needs to be isolated. Errors of isolating the wrong eye will have as the result that the application is no use to the user.

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Visual Impairments

Definitions of Visual Impairment

Definition by The European Blind Union

The definitions of blindness and partial sight, as well as the registration criteria vary from one European country to another. EBU adopts in principle the definitions used by the World Health Organisation (WHO) for blindness and partial sight. At the same time EBU advocates the importance of using the so called 'functional sight' parameters in addition to the WHO definitions when determining the support a blind or partially sighted person needs.

The term ‘visual impaired' is used to indicate blind plus partially sighted people together.

Partially sighted and low vision are used as equal indication of limited sight. [20]

Definition by World Health Organisation

There are 4 levels of visual function, according to the International Classification of Diseases -10 (Update and Revision 2006):

- normal vision
- moderate visual impairment
- severe visual impairment
- blindness
    - profound low vision
    - near total blindness
    - total blindness

Moderate visual impairment combined with severe visual impairment are grouped under the term “low vision”: low vision taken together with blindness represents all visual impairment. [21]

Definitions of Low Vision - The World Wide Web Consortium (W3C)

What is Low Vision? Some definitions include:

"Low vision refers to a visual impairment that is not correctable through surgery, pharmaceuticals, glasses, or contact lenses. This condition is often characterized by partial sight, such as blurred vision, blind spots or tunnel vision, but also includes legal blindness. Low vision can impact people of all ages, but it is associated primarily with adults over the age of 60. It is estimated that between 3.5 million to five million people in the U.S. suffer from low vision." [22]

"If you have been told you have low vision, it means you still have some good usable vision..." [23]

"Low vision means that even with regular glasses, contact lenses, medicine, or surgery, people find everyday tasks difficult to do." [24]

"Low vision is a condition caused by eye disease, in which visual acuity is 20/70 or poorer in the better-seeing eye and cannot be corrected or improved with regular eyeglasses." [25]

"...vision between 20/60 and 20/190 it is called being partially sighted or having low vision. If the change in vision is to 20/200 or worse, the person will still keep some vision but will be classified as "blind" (some people may be classified as blind if their field of vision, or the area that they can see, is less than 20° across--even if their vision is better than 20/200)." [26]

"Anyone with non correctable reduced vision is visually impaired, and can have a wide range of problems. The World Health Organization uses the following classifications of visual impairment. When the vision in the better eye with best possible glasses correction is:

- 20/30 to 20/60 is considered mild vision loss, or near-normal vision
- 20/70 to 20/160 is considered moderate visual impairment, or moderate low vision
- 20/200 to 20/400 is considered severe visual impairment, or severe low vision
- 20/500 to 20/1,000 is considered profound visual impairment, or profound low vision
- less than 20/1,000 is considered near-total visual impairment, or near total blindness
- no light perception is considered total visual impairment, or total blindness" [27]

Visual functions

Visual acuity

Ability to resolve fine detail; measure of sharpness or clarity of vision. It can be measured with Snellen charts – the individual recognizes standardized letters from a certain distance. Near and distant visual acuity is measured. Visual acuity is normal, when a person has 6/6 visual acuity or 100% sharp sight.

Classification of visual impairment - visual acuity (World Health Organisation):

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1. category: moderate low vision (30% - 10% visual acuity)
2. category: severe low vision (9,9% - 5% visual acuity)
3. category: profound low vision (4,9 % - 2% visual acuity)
4. category: near total blindness (1,9% visual acuity - light perception)
5. category: blindness (no light perception)

Visual field

Entire region of space off to all sides that is visible, when the person is steadily looking straight ahead; visual field is measured in degrees. Visual field is normal, when the horizontal extent of the normal vision field for one eye is 160 degrees, for both eyes together 190 degrees and the vertical extent is 115 degrees.

Better vision is present in central visual field, poorer vision in peripheral visual field. Visual field defect:

- beyond about 30 degrees eccentricity are peripheral,
- at about 30 degrees eccentricity are mid peripheral and
- within 30 degrees are central.

Classification of visual impairment - visual field (World Health Organisation):

1. category: 9,9% - 5% visual acuity OR 20 – 10 degrees from the point of fixation (with or without 100% visual acuity) - concentric defects
2. category: 4,9 % - 2% visual acuity OR 10 – 5 degrees from the point of fixation(with or without 100% visual acuity) - concentric defects
3. category: 1,9% visual acuity - light perception OR 5 degrees or less visual from the point of fixation (with or without 100% visual acuity) - concentric defects

Contrast sensitivity

Small differences in brightness between an object and its background.

Measured in percent (100 – 0%), for example using letter charts – letters are the same size, but vary in contrast from black to faint grey on a white background.

The higher a person’s contrast sensitivity, the lower the levels of contrast the person can detect.

More contrast is needed to see fine detail, than to see gross detail.

Light sensitivity

Varies by eye condition and among persons with the same eye condition.

Some prefer more amount of light to function optimally, others little amount of light.

One person can have different light preference: task lighting (light focused directly on a near task) and ambient lighting (indoors and outdoors).

Photophobia - abnormal sensitivity to light (any type).

Color discrimination

People with normal vision have the most impairments in color vision. Color vision can be damaged because of serious eye conditions, that cause reduced visual acuity and other visual difficulties. In rare cases impaired color vision is caused by a brain disorder.

Color discrimination is tested with plate tests – recognizing letters, numbers, shapes formed by color dots (surrounded by dots, that have colors commonly confused) on a series of pages.

Oculomotor control

The control of eye movement and position is often disrupted when vision is impaired.

Eye movement control means ability to fixate steadily on an object.

Accommodation

Distance vision requires less ocular focusing power than near vision. The flexibility of the lens for looking at long and short distances – is an ability to accommodate and see clearly. Accommodation is connected with visual acuity – they have to look closer than sighted people. Signs of accommodation insufficiency: headaches, eyestrain. Wearing reading glasses for near vision helps in problems with accommodation.

Vision center in brain can be disrupted because of brain injuries or disorders. It is difficult to reliably measure visual abilities. Damage causes visual functioning is sensitive to fatigue, minor illnesses, anxiety, medications, poor lighting, low contrast, crowding.

Refractive errors

The clearest image is formed in an eye, when light from the object being viewed passes through the optical (or focusing) elements of the eye (cornea and lens) and is in perfect focus when it reaches the retina - this condition is called emmetropia. The combined focal length of the cornea and lens matches the length of the eye.

Refractive error is a condition in which rays are not brought into focus on the retina as a result of a defect in the shape of the eye or its optical elements.

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- Myopia: nearsightedness - the focal length of optical elements are shorter than the length of the eye. Uncorrected myopia: distance vision is blurred, objects held at some close distance may be clear.
- Hyperopia: farsightedness - the focal length of optical elements is longer than the length of the eye. Uncorrected hyperopia: distance vision is clear and objects held at some close distance may not be clear. With sufficient accommodation they may see clearly at distance and less likely, at near as well.
- Astigmatism: the cornea is curved not like the surface of a sphere. Uncorrected astigmatism: vision is blurred for object at all distances, with some edges more blurred than others. Astigmatism commonly occurs with myopia and hyperopia.

Two persons can have the same eye condition, but can use their vision differently. Functional vision assessment describes the use of vision of each individual.

Eye conditions [28 - 31]

Achromatopsia (rod monochromacy)

Colorblindness - Normal rod photoreceptors in retina; few and abnormal cone photoreceptors; nystagmus, photophobia

Stability of condition	Stable
Visual acuity	20 % - 10 %, possible central scotomas
Refractive error	Astigmatism
Peripheral visual Fields	Normal
Contrast sensitivity	Reduced
Preferred task lighting	Dim - medla
Sensitivity to ambient light	Very high
Colour vision	None. Colors may be seen as shades of grey.
Accomodation	Varies with age
Adaptations	Adapted color-dependent activities, support of eccentric viewing, high contrast materials, use of sunglasses, visors, hats outdoors and indoors, reduced or diffused lighting

Possible implications on Gaze estimation system	Nystagmus - unsteady eye fixation, eyeglasses, sunglasses, visors - throwing shadow on eyes, reduced ambient lighting, possible eccentric viewing

Albinism

Total or partial absence of pigment, causing abnormal optic nerve development. Translucent irises, pale fundus, macular hypoplasia, nystagmus, photophobia, muscle imbalance, eye fatigue with close or detailed work, reduced depth perception

Stability of condition	Stable
Visual acuity	30 % - 5 %, possible central scotomas
Refractive error	Astigmatism
Peripheral visual Fields	Normal
Contrast sensitivity	Varies
Preferred task lighting	Dim to intermediate
Sensitivity to ambient light	High to very high
Colour vision	Varies
Accomodation	Varies with age
Adaptations	Magnification (hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.), close viewing, high contrast materials, sunglasses, visors, or hats outdoors and indoors, lighting from behind, reduced glare, frequent breaks.
Possible implications on Gaze estimation system	Nystagmus - unsteady eye fixation, eye- and sunglasses, noir filters, visors - throwing shadow on eyes, reduced ambient lighting, possible eccentric viewing, eye muscle imbalance

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Amblyopia

Reduced visual functioning in one eye (aka. 'lazy eye'), which causes the person to use one eye instead of both. Strabismus is a common cause of amblyopia. Cause can also be refraction error on one eye or cataract on one eye. Monocular vision causes reduced depth perception

Stability of condition	With young children, eye exercises, occlusion or patching of one eye or surgery may help. Low vision
Visual acuity	Varies
Refractive error	Varies
Peripheral visual Fields	Usually visual field preserved
Contrast sensitivity	Normal
Preferred task lighting	Normal
Sensitivity to ambient light	Normal
Colour vision	Normal
Accomodation	Varies with age
Adaptations	Frequent breaks, seating should favor functional eye, familiarization with new environments, time to adjust in new situations, may need adaptations for activities requiring visual-motor coordination.
Possible implications on Gaze estimation system	Both eyes may not work together equally as a team (different directions of eye fixation). Monocular vision.

Aniridia

A rare genetic disorder that causes absence of all or part of the iris, usually affecting both eyes. Photophobia. Often connected to amblyopia, cataracts and glaucoma. Sometimes associated with displaced lens, under-developed retina, and nystagmus.

Stability of condition	Cataract or glaucoma may develop.
Visual acuity	10 % - 5 %
Refractive error	Astigmatism
Peripheral visual Fields	Varies
Contrast sensitivity	Reduced
Preferred task lighting	Dim to intermediate
Sensitivity to ambient light	High to very high
Colour vision	Normal
Accomodation	Reduced
Adaptations	Contact lenses with an artificial iris, tinted spectacles, or bioptic glasses may be prescribed. Iris and stem cell implant surgeries are possible. May need to use sunglasses, visors, or hats outdoors and indoors as well, allow time for adjustment to lighting changes. Provide seating with back to windows, reduced glare, provide lighting from behind, reduced or diffused lighting, lamps with rheostats and adjustable arms. Magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.), black backgrounds and white san serif fonts.
Possible implications on Gaze estimation system	nystagmus - unsteady eye fixation; eye glasses, sunglasses, visors (throwing shadow on eyes), reduced ambient lighting

Anophthalmia

Absence of one or both eyeballs. Monocular vision: reduced field, reduced depth perception; blindness Often this eye is malformed.

Stability of condition	Stable
Visual acuity	100% on one eye - no light perception on both eyes
Refractive error	Varies

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Peripheral visual Fields	Varies
Contrast sensitivity	Varies
Preferred task lighting	Varies
Sensitivity to ambient light	Varies
Colour vision	Varies
Accomodation	Varies with age.
Adaptations	Prosthetic eyes. May need visual efficiency training to develop scanning skills. Seating and presentation of materials should favor functional eye.
Possible implications on Gaze estimation system	Prosthetic eye - no eye movement. Monocular vision or total blindness.

Buphthalmos

Enlarged eyeballs. Can cause enlargement and increased depth of the anterior chamber, damage to the optic disc, and/or increased diameter and thinning of the cornea. Photophobia. Eye pain.

tability of condition	Blindness occurs if left untreated.
Visual acuity	Reduced central acuity
Refractive error	Myopia
Peripheral visual Fields	Varies, it is reduced because glaucomatous.
Contrast sensitivity	Reduced
Preferred task lighting	Dim to intermediate
Sensitivity to ambient light	High to very high
Colour vision	Reduced
Accomodation	Varies with age.
Adaptations	May need to use sunglasses, visors, or hats outdoors and indoors. Reduced or diffused lighting from

	behind. More time for adjustment to lighting changes. High contrast materials. Magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). Enlarged printed materials. Close viewing.
Possible implications on Gaze estimation system	Eye- and sunglasses, visors - throwing shadow on eyes, reduced ambient lighting

Coloboma

A notch or other defects involving the iris, lens, retina, choroid, and/or optic nerve. A "Keyhole" pupil often occurs. Associated with cataracts, nystagmus, strabismus and glaucoma (later in life).

Stability of condition	Usually stable, retinal complications may develop
Visual acuity	100 % - 5 %
Refractive error	Varies
Peripheral visual Fields	Depends on retinal area involved
Contrast sensitivity	Varies
Preferred task lighting	Varies
Sensitivity to ambient light	Varies
Colour vision	Normal
Accomodation	Varies with age
Adaptations	High contrast materials, magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.), average to bright light, reduced glare, may need to use sunglasses, visors, or hats outdoors and indoors as well (if iris is affected)
Possible implications on Gaze estimation system	Nystagmus - unsteady eye movements, strabismus - both eyes don't work together equally as a team (different directions of eye fixation), eye- and/or

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	sunglasses, reduced ambient lighting, uncertainty about the centroid of the pupil

Congenital cataract (with cataract removal)

Opacity or cloudiness of the lens, which restricts passage of light to the retina; usually bilateral. Pupil may appear white. Mature cataracts are usually removed surgically, requiring lens implants or contact lenses. Aphakia, deprivation amblyopia; nystagmus may be present. Photophobia may be present.

Stability of condition	Glaucoma may develop
Visual acuity	50 % - 5 %
Refractive error	High hyperopia
Peripheral visual Fields	Normal (unless advanced glaucoma also)
Contrast sensitivity	Reduced
Preferred task lighting	Varies
Sensitivity to ambient light	Moderate
Colour vision	Normal or reduced color discrimination
Accomodation	Absent if lens removed
Adaptations	Support of the wearing of any prescribed lenses. Magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). Enlarged printed materials. Close viewing. Support of eccentric viewing. May need to use sunglasses, visors, or hats outdoors and indoors. May need reduced or diffused lighting, lighting from behind. May need lamps with rheostats and adjustable arms. Reduced glare.
Possible implications on Gaze estimation system	Eye-, sunglasses, visors, nystagmus - unsteady eye movements

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CVI - Cortical (cerebral) visual impairment

A neurological visual disorder resulting from damage to the optic nerve and/or parts of the brain that process and interpret visual information (i.e., visual cortex), usually accompanied by other neurological disorders. Highly variable visual functioning.

Stability of condition	Can improve at an early age
Visual acuity	Varies
Refractive error	Varies
Peripheral visual Fields	Nearly always prefered
Contrast sensitivity	Reduced
Preferred task lighting	Varies
Sensitivity to ambient light	High in about ⅓ of cases
Colour vision	May prefer primary colors
Accomodation	Varies with age
Adaptations	Use of movement to increase visual attention, use of preferred color to increase visual attention. Present visual information in preferred visual field. Present visual information on a solid background (e.g., black or white cloth). Use of bright, high contrast materials. Increase line spacing and white space on a page of text and/or images to reduce visual clutter and complexity. Use high contrast templates to reduce the amount of information seen at one time. Close viewing. Vision efficiency training. Frequent breaks from visual tasks. High illumination from behind. Sunglasses, visors or hats may be worn indoors. Support use of one sense at a time. Reduce visual, auditory, and tactile distractions. Extra time to respond. Use of consistent visual cues across settings.
Possible implications on Gaze estimation system	Eccentric viewing, visual latency: delayed visual processing - in directing gaze, identification, recognition, and/or discrimination. Difficulties with discrimination and interpretation of complex visual

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	information. Poor visual attention. Reduced ambient lighting.

Diabetic Retinopathy

Changes in the blood vessels of the retina, causing haemorrhaging in the retina and vitreous. o Abnormal retinal swelling and/or new blood vessel growth; glaucoma can develop. o Double vision

Stability of condition	Laser treatment or surgery may stabilize; it may lead to retinal detachment and blindness.
Visual acuity	100 % - no light perception
Refractive error	aries if sugar levels are dysregulated
Peripheral visual Fields	Depends on retinal areas damaged
Contrast sensitivity	Reduced
Preferred task lighting	Moderate
Sensitivity to ambient light	Moderate to high
Colour vision	Reduced
Accomodation	Reduced
Adaptations	dequate high quality lighting (e.g., lamps with rheostats and adjustable arms), high contrast materials, magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.), large button/key technology may be helpful, training in use of auditory materials may be needed due to loss of vision and tactile sensitivity. Training in use of speech recognition input software may be helpful. Precautions related to decreased sensitivity in hands and feet (e.g., burns, cuts, falls)
Possible implications on Gaze estimation system	Compensatory head posture or fixational point of viewing due to different extend and position of reduced visual field, eyeglasses-, sunglasses, reduced ambient lighting

Diplopia

Muscular defect that restricts the ability of the eyes to work together. Can be a result of strabismus. It causes double and blurring vision, as the image from one eye is imposed on the image from the other eye. Corrective lenses may be prescribed. Suppression (the brain ignores the image from one eye) of the image from one eye, causing monocular vision. Those with childhood strabismus almost never complain of diplopia, while adults who develop strabismus almost always do. Binocular or monocular diplopia.

Stability of condition	Left untreated, this condition can develop into amblyopia.
Visual acuity	Varies
Refractive error	Varies (can be a cause of monocular diplopia)
Peripheral visual Fields	Normal
Contrast sensitivity	Reduced
Preferred task lighting	Normal
Sensitivity to ambient light	Normal
Colour vision	Normal
Accomodation	Varies with age
Adaptations	High contrast materials. Reduced glare. Extended time to adjust to new situations. Frequent breaks from visual tasks. Familiarization with new environments.
Possible implications on Gaze estimation system	Impaired function of the extraocular muscles of both eyes - both eyes are still functional, but they cannot turn to target the desired object; possible monocular vision; eye-glasses

Glaucoma

Optic nerve atrophy due to elevated intraocular pressure, insufficient blood flow, or other processes. Eye redness. Hazy cornea. Photophobia.

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Stability of condition	Often stabilized or slowed with treatment. Untreated glaucoma can lead to degeneration of the optic disk and blindness.
Visual acuity	Reduced in advanced cases
Refractive error	Myopia more common
Peripheral visual Fields	Reduced in mid- and then far peripheral
Contrast sensitivity	Reduced
Preferred task lighting	Moderate
Sensitivity to ambient light	Moderate
Colour vision	Reduced
Accomodation	Varies with age
Adaptations	Use of sunglasses, visors, or hats in bright sunlight and bright lighting indoors. Allow time for adjustment to lighting changes. Reduced glare. Adequate lighting (e.g., lamps with rheostats and adjustable arms). High contrast materials. May benefit from magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). May need visual efficiency training to develop scanning skills. Frequent breaks from visual tasks. May need instruction in tactile learning and braille. Teachers must be alert to signs of pain and increased ocular pressure.
Possible implications on Gaze estimation system	Tunnel vision - possible simultaneous movement of head and eyes at visual searching; eye-, sunglasses, visors, eye redness, hazy cornea.

Hemianopsia

Blindness or impaired vision in one half of the visual field in one or both eyes.

Stability of condition	Stable
Visual acuity	100% in the unaffected field(s)
Refractive error	Varies

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Peripheral visual Fields	If both eyes are affected, vision loss may occur on the same side in both nasal fields, or in both temporal fields.
Contrast sensitivity	Normal
Preferred task lighting	Normal
Sensitivity to ambient light	Normal
Colour vision	Normal
Accomodation	Varies with age
Adaptations	Visual efficiency training to develop scanning skills
Possible implications on Gaze estimation system	Compensatory head and eye movements at visual searching due to different visual field defect

Keratoconus

Thinning and distortion of cornea with possible scarring; Degenerative disorder in which the cornea thins and takes on a conical shape. Often bilateral but not symmetrical, so vision may be significantly better in one eye than the other. o Sometimes associated with retinitis pigmentosa, Down’s syndrome, Marfan’s syndrome, and Aniridia.

Stability of condition	Slowly progressive; may require surgery
Visual acuity	100% - 30 % with contact lenses
Refractive error	Contact lenses usually required (myopia, astigmatism)
Peripheral visual Fields	Normal
Contrast sensitivity	Reduced
Preferred task lighting	Varies
Sensitivity to ambient light	Varies
Colour vision	Normal
Accomodation	Varies with age

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Adaptations	Reduced glare. Diffused lighting. Lamps with rheostats and adjustable arms. High contrast materials. Magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.)
Possible implications on Gaze estimation system	/

Macular degeneration (age-related, myopic, juvenile, Stargardt's disease, histoplasmosis, toxoplasmosis)

Atrophy and/or scarring of retina at macula; abnormal new blood vessels can form

Stability of condition	Usually progresses for several years
Visual acuity	80 % - 2 %, central scotomas
Refractive error	Varies
Peripheral visual Fields	Normal
Contrast sensitivity	Reduced
Preferred task lighting	Bright
Sensitivity to ambient light	High
Colour vision	Reduced
Accomodation	Varies with age
Adaptations	Support of eccentric viewing, Support use of sunglasses, hats, or visors in bright sunlight, allow time for adjustment to lighting changes. Adequate lighting (e.g., lamps with rheostats and adjustable arms). Diffused lighting may allow the pupil to enlarge so that more area can be viewed. Close viewing. Magnification (e.g., hand-held magnifier, electronic magnifier with light text on dark background, screen enlargement software, telescope for distance viewing etc.). Reduced glare. High contrast materials. Seating in front with back to

	window. Adapted color-dependent activities. Frequent breaks from visual tasks.
Possible implications on Gaze estimation system	Eccentric viewing, eye-, sun-glasses, visors, reduced ambient lighting

Microphthalmia

A hereditary, developmental disorder that causes one or both eyes to be abnormally small Photophobia.

Stability of condition	Fluctuating visual abilities.
Visual acuity	Varies
Refractive error	Varies
Peripheral visual Fields	Varies
Contrast sensitivity	Varies
Preferred task lighting	Normal
Sensitivity to ambient light	Varies
Colour vision	Varies
Accomodation	Varies
Adaptations	High contrast. Reduced glare. Average to bright light. May need magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). Expectations may need to be adjusted due to the frustration related to fluctuating visual abilities. Frequent breaks from visual tasks
Possible implications on Gaze estimation system	Small eyeballs, fluctuating visual abilities

Nystagmus (congenital)

The eyes appear to be in constant motion; jiggling from side to side. Involuntary and continual eye movement (movements can increase under certain stressful situations or can decrease if they look in certain direction – null point) which can be horizontal, vertical, circular, or mixed. Inability to maintain steady fixation. Frequency and

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amplitude of nystagmus varies. Stripes and other patterns, stress may increase the rate of the nystagmus.

Stability of condition	Stable
Visual acuity	100% - 15 %
Refractive error	Varies
Peripheral visual Fields	Varies
Contrast sensitivity	Normal
Preferred task lighting	Normal
Sensitivity to ambient light	Normal
Colour vision	Normal
Accomodation	Varies with age
Adaptations	Shifting gaze or tilting the head may help to find the null point at which the nystagmus slows. Frequent breaks from close visual tasks. Vary visual tasks. Adequate lighting. Good contrast. Instruction in stress reduction strategies
Possible implications on Gaze estimation system	Eyeglasses, unsteady eye fixation

Optic Atrophy

Damaged optic nerve limits or stops transmission of visual information from the eye to the brain. It is evidenced by a pale optic disc and reduced pupillary response. Glaucoma, tumors can cause optic atrophy. May develop photophobia. Fluctuating visual performance.

Stability of condition	Type 1 optic atrophy is progressive.
Visual acuity	Reduced visual acuity - no light perception
Refractive error	Varies
Peripheral visual Fields	Reduced
Contrast sensitivity	Reduced

Preferred task lighting	High illumination
Sensitivity to ambient light	Varies
Colour vision	Reduced
Accomodation	Varies with age
Adaptations	High contrast. Enlarged printed materials. May need magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). Avoid visual clutter (present visual information in isolation, avoid busy backgrounds, provide opportunities to confirm or clarify visual information through tactile exploration. May benefit from verbal descriptions to help make sense of visual information. May need adapted color dependent activities. May need instruction in tactile learning and braille
Possible implications on Gaze estimation system	Fluctuating visual functioning

Optic Nerve Hypoplasia

Disorders of early brain development. Congenital, nonprogressive condition in which the optic nerve is under-developed and small. It may affect one or both eyes, and when both are affected, side-to-side nystagmus is frequently present. The incidence of strabismus is increased. Learning disability, autism, cerebral palsy, and intellectual developmental delays can occur with ONH.

Stability of condition	During the first few years of life, vision may improve as the brain continues to develop. Stable.
Visual acuity	Reduced visual acuity. May have better acuity In one eye than in the other.
Refractive error	Varies
Peripheral visual Fields	Variable field restrictions
Contrast sensitivity	Reduced
Preferred task lighting	High illumination

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Sensitivity to ambient light	Varies
Colour vision	Reduced
Accomodation	Varies with age
Adaptations	High contrast. Enlarged printed materials. May need magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). Avoid visual clutter (present visual information in isolation, avoid busy backgrounds, provide opportunities to confirm or clarify visual information through tactile exploration. May benefit from verbal descriptions to help make sense of visual information. May need instruction in tactile learning and braille.
Possible implications on Gaze estimation system	Nystagmus - unsteady eye fixation, strabismus

Photophobia

Abnormal sensitivity to light (any type) It is usually associated with an eye disease or disorder (e.g., iritis, ocular albinism, aphakia, aniridia, dislocated lens, cataracts, glaucoma, etc.). Many people experience mild photophobia that is unrelated to another eye condition. Severe photophobia can be quite painful, even in relatively dim light.

Stability of condition	Stable
Visual acuity	Varies
Refractive error	Varies
Peripheral visual Fields	Normal
Contrast sensitivity	Varies
Preferred task lighting	Dim
Sensitivity to ambient light	Moderate to very high
Colour vision	Normal
Accomodation	Varies with age

Adaptations	May need to use sunglasses, visors, or hats outdoors and indoors as well. Reduced or diffused lighting. Provide lighting from behind. Use of shielded lamps with rheostats and adjustable arms). Reduced glare. May benefit from use of noir sunglasses and/or filters (colored overlays) when reading. May need breaks from visual tasks or rest periods in a darkened area.
Possible implications on Gaze estimation system	Reduced ambient lighting, visors - throwing shadow on eyes, noir filters, sunglasses.

Ptosis

Drooping (sagging) of the eyelid It may affect upper and/or lower lids and one or both eyes. Ptosis is usually due to weakness of the muscles that control the eyelids, damage to the nerves that control these muscles, or very loose skin of the upper eyelids.

Stability of condition	Long-term reduction of visual field can cause amblyopia
Visual acuity	Varies
Refractive error	Varies
Peripheral visual Fields	Severe ptosis obscures the upper visual field
Contrast sensitivity	Normal
Preferred task lighting	Normal
Sensitivity to ambient light	Normal
Colour vision	Normal
Accomodation	Varies with age
Adaptations	May need visual efficiency training to develop scanning skills
Possible implications on Gaze estimation system	Compensatory head and eye movements at visual searching due to upper visual field defect

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Retinal Detachment (similar implications: Retinal Dysplasia - abnormal development or growth of the retina)

An emergency situation in which parts of the retina pull away from the underlying tissue that nourishes it and from the supporting structure of the eye. May develop strabismus.

Stability of condition	Detachments can be repaired if treated within 24-72 hours, but detached parts deteriorate rapidly.
Visual acuity	Varies. Possible central field loss.
Refractive error	Myopia
Peripheral visual Fields	Scotomas; variable field loss
Contrast sensitivity	Reduced
Preferred task lighting	High illumination
Sensitivity to ambient light	Varies
Colour vision	Reduced
Accomodation	Varies with age
Adaptations	Magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). May need visual efficiency training to develop scanning skills. Support of eccentric viewing. High illumination. Reduced glare. Seating in front with back to window. Frequent breaks from visual tasks.
Possible implications on Gaze estimation system	Eccentric viewing, eyeglasses, compensatory head and eye movements at visual searching due to different visual field defect.

Retinitis Pigmentosa and Leber's amaurosis

Degeneration of the retina. Photoreceptor degeneration usually begins in mid periphery and extends outward and inward; nystagmus may be present. Night blindness. Retinal detachment can occur.

Stability of condition	Slowly progressive over decades

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Visual acuity	In advanced disease 50 % - no light perception; acuity loss may be early in some uncommon form of this condition
Refractive error	Varies
Peripheral visual Fields	Mid- peripheral, then tunnel vision, then complete field loss
Contrast sensitivity	Reduced
Preferred task lighting	Moderate to bright
Sensitivity to ambient light	High
Colour vision	Reduced
Accomodation	Varies with age
Adaptations	Reduced glare. Noir lenses or overlay filters. Video magnifier for maximum contrast. Visual efficiency training in organized search (grid) patterns. Central field loss: magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). Peripheral field loss: increase viewing distance to see more area.
Possible implications on Gaze estimation system	Compensatory eye and head position, eyeglasses, noir filters, reduced ambient lighting

Retinopathy of prematurity

Incomplete retinal development and dragging of macula; nystagmus may be present. Strabismus. Partial or complete retinal detachment.

Stability of condition	Cataract and glaucoma may develop
Visual acuity	100 % - no light perception
Refractive error	Myopia
Peripheral visual Fields	Varies (scotomas)
Contrast sensitivity	Reduced
Preferred task lighting	Moderate

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Sensitivity to ambient light	Moderate
Colour vision	Varies
Accomodation	Varies with age
Adaptations	May need visual efficiency training to develop scanning skills. Visual efficiency training in organized search (grid) patterns. Adequate to high illumination (e.g., lamps with rheostats and adjustable arms). Reduced glare. Frequent breaks from visual tasks. May benefit from access to auditory materials and need instruction in tactile learning and braille. May benefit from magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). Reduced glare. Support of eccentric viewing.
Possible implications on Gaze estimation system	Eyeglasses, eye muscle imbalance, nystagmus, compensatory head and eye position due to different visual field defects

Scotoma

A portion of the visual field that is blind or partially blind and surrounded by relatively normal vision, depending on the presence of other eye conditions. Scotomas can occur in any part of the visual field. Photophobia.

Stability of condition	Stable
Visual acuity	Reduced, depends on the position of scotoma
Refractive error	Varies
Peripheral visual Fields	Reduced, depends on the position of scotoma.
Contrast sensitivity	Varies
Preferred task lighting	Varies
Sensitivity to ambient light	High
Colour vision	Varies
Accomodation	Varies with age

Adaptations	Visual efficiency training to develop scanning skills. Support of eccentric viewing. Seating and presentation of work should favor more functional eye. May need to use sunglasses, visors, or hats outdoors and indoors. Reduced glare. May need lighting from behind using adjustable lamps with rheostats and adjustable arms. Magnification (e.g., hand-held magnifier, electronic magnifier, screen enlargement software, telescope, etc.). May benefit from enlarged printed materials. May benefit from close viewing. High contrast materials.
Possible implications on Gaze estimation system	Compensatory head and eye position due to different visual field defects, visors, eye- and sunglasses

Strabismus

An inability to look at the same point in space with both eyes at the same time. One eye points directly at the object, other eye point in another direction.

- Monocular vision if congenital.
- Double vision in case of acquired strabismus.
- It can be caused by a defect in the extraocular muscles (“tropias” - muscle imbalances are always present) or in the part of the brain that controls eye movement (“phorias” - not always present, they tend to manifest when the person is tired).
- Eso – turned inward/nasal (esophoria and esotropia)
- Exo – turned outward/temporal (exophoria and exotropia)
- Hyper – turned upward (hyperphoria and hypertropia)
- Hypo – turned downward (hypophoria and hypotropia)

Stability of condition	Treatments can be effective for young children: eye exercises, occlusion of the better eye, medications, and surgery. Otherwise stable.
Visual acuity	Varies
Refractive error	Varies
Peripheral visual Fields	Reduced due to monocular vision
Contrast sensitivity	Normal
Preferred task lighting	Normal

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Sensitivity to ambient light	Normal
Colour vision	Normal
Accomodation	Varies with age
Adaptations	Vision efficiency training in scanning, tracking, and tracing. Prismatic glasses may be prescribed to increase field of vision.
Possible implications on Gaze estimation system	Difficulty fixating. May have difficulty scanning, tracking, and tracing. Difficulty following fast-moving objects. Difficulty making eye contact.

Stroke

Brain damage often limited to one hemisphere; nystagmus with oscillopsia may occur

Stability of condition	Cataract and glaucoma may develop
Visual acuity	100 % - no light perception
Refractive error	Myopia
Peripheral visual Fields	Varies
Contrast sensitivity	Reduced
Preferred task lighting	Moderate
Sensitivity to ambient light	Moderate
Colour vision	Varies
Accomodation	Varies with age
Adaptations	Visual efficiency training to develop scanning skills. Seating and presentation of work should favor the functional eye.
Possible implications on Gaze estimation system	Unsteady eye fixation, compensatory head and eye position, eyeglasses, monocular vision

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Trauma

Various implications can from deduced to a trauma.

Stability of condition	Varies
Visual acuity	100% - no light perception
Refractive error	Varies
Peripheral visual Fields	Varies
Contrast sensitivity	Varies
Preferred task lighting	Varies
Sensitivity to ambient light	Varies
Colour vision	Varies
Accomodation	Varies with nature of damage and age
Adaptations	Varies
Possible implications on Gaze estimation system	Prosthetic eyes - no eye movement, monocular vision

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Eye conditions impact on eye/gaze tracking system [32-35]

<table>
<tr><th colspan="2">Visual function</th></tr>
<tr><td colspan="2">Low visual acuity, refractive error, absence or low accommodation function</td></tr>
<tr><th>Possible implications on eye/gaze tracking system</th><th>Eye condition, disease</th></tr>
<tr><td>- Wearing eye glasses

- A third can not always see the visual impairment.</td><td>Most of people with VI have lower visual acuity and refractive error.

Accommodation problem - common loss of flexibility of the lens that occurs in adulthood, usually at the age of 40 (presbyopia).

At earlier age - aphakia - removed lens because of congenital cataract.</td></tr>
<tr><th colspan="2">Visual function</th></tr>
<tr><td colspan="2">Visual field defect

- central

- peripheral

- scotomas on visual field</td></tr>
<tr><th>Possible implications on eye/gaze tracking system</th><th>Eye condition, disease</th></tr>
<tr><td>- Wearing eye glasses - prisms to enlarge visual fields, eccentric viewing

- compensatory head and eye position to improve visual functioning

- a third can not always see the visual impairment.</td><td>Central visual defects: achromatopsia, albinism, macular degeneration, retinal detachment, retinitis pigmentosa

Peripheral visual field defects: ptosis (upper visual field restriction), amblyopia, strabismus (monocular vision), glaucoma (tunnel vision), coloboma, hemianopsia, retinitis</td></tr>
</table>

	pigmentosa) Scotomas: diabetic retinopathy, coloboma, retinal detachment, retinopathy of prematurity
Visual function	
Light sensitivity	
Possible implications on eye/gaze tracking system	**Eye condition, disease**
- Wearing sunglasses, noir filters, tinted glasses, visors, need reduced ambient lighting - A third can not always see the visual impairment.	Photophobia, achromatopsia, albinism, aniridia, buphthalmos, coloboma (if the iris is affected), cataract, CVI (in ⅓ cases), glaucoma, macular degeneration, microphthalmos, retinitis pigmentosa, buphthalmos
Visual function	
Abnormal oculomotor control	
Possible implications on eye/gaze tracking system	**Eye condition, disease**
- Muscle imbalance. - Unsteady eye fixation. - Inability to look at the same point in space with both eyes at the same time. - Monocular vision. - A third can see the visual impairment	Nystagmus (is associated with many eye diseases/conditions - achromatopsia, aniridia, albinism, coloboma, cataract, retinopathy of prematurity, optic nerve hypoplasia) - unsteady eye fixation, constant movements of eye. Strabismus (is also associated, connected with other eye diseases, conditions: amblyopia, coloboma, diplopia, retinal detachment, stroke, retinopathy of prematurity
Visual function	
Missing eye, small eyes	

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<table>
<tr><th>Possible implications on eye/gaze tracking system</th><th>Eye condition, disease</th></tr>
<tr><td>- Prosthetic eyes - no eye movement; monocular vision; difficult location of eyes (small eyes)

- A third can see the visual impairment</td><td>Missing eye: trauma, tumor (retinoblastoma), anophthalmia

Small eyes: microphthalmia</td></tr>
<tr><th colspan="2">Visual function</th></tr>
<tr><td colspan="2">Stability of visual functioning</td></tr>
<tr><th>Possible implications on eye/gaze tracking system</th><th>Eye condition, disease</th></tr>
<tr><td>- Fluctuating visual functioning

- A third can not always see the visual impairment</td><td>CVI, microphthalmia, optic atrophy</td></tr>
</table>

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Existing Surveys on Visual Impairments and Gaze Tracking Applications

In the existing surveys eye tracking is considered as a successful tool for evaluation of visual ability of individuals with visual impairment. It can be used for better understanding of the visual search mechanisms of individuals with glaucoma.

Articles describe the negative effects of wearing corrective lenses while using eye trackers and offer some solutions for participants with eye glasses.

Articles suggest, that eye-tracking data quality, e.g. the accuracy of the recorded gaze position and the amount of data loss, deteriorates (compared to well-trained participants in chinrests) when the participant is unrestrained and assumes a non-optimal pose in front of the eye-tracker.

1. Evaluating Silent Reading Performance with an Eye Tracking System in Patients with Glaucoma

The severity of visual field defects may influence some aspects of reading performance. At least concerning silent reading, the visual field of the worse eye is an essential element of smoothness of reading.

Used eye tracking device: Eye movements were monitored using a Tobii TX300 eye tracking device (Tobii Technology, Danderyd, Sweden). [36]

2. Using Eye Tracking to Assess Reading Performance in Patients with Glaucoma: A Within-Person Study

Seccade rate in reading can be measured by an eye tracker, which can be an useful surrogate for reading performance.

Glaucoma will take longer to read with worse eye comparing to better eye.

Used eye tracking device: EyeLink 1000 (SR Research Ltd., Mississauga, Ontario, Canada). [37]

3. Eye-Tracking as a Tool to Evaluate Functional Ability in Everyday Tasks in Glaucoma

Among the state-of-the art algorithms for head-mounted and remote eye-tracking, ExCuSe and ElSe, two decision-based approaches based on edge detection and ellipse fitting, show very high accuracy combined with real-time processing capability.

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When eye-trackers with low sampling rates up to 60 Hz are incorporated, the PupilNet algorithm based on advanced machine learning techniques (i.e., Convolutional Neural Networks), achieves even higher robustness with regard to the above-mentioned sources of noise.

To date, most eye movement analytical approaches are based on time-integrated measures, such as the average fixation duration, or the number of fixations directed towards a specific region of interest.

With the development of more sophisticated eye-tracking technology, assessment of eye movements provides a powerful tool for better understanding the visual search mechanisms of individuals with glaucoma and their implications for everyday tasks. Combined with virtual reality technology, eye-tracking offers the possibility for focused eye movement research under standardized experimental conditions and the development of personalized solutions to assist glaucoma patients.

Video-based eye tracking: head-mounted, mobile eye-tracking technology (e.g., Dikablis Mobile eye-tracker, Pupil Labs eye-tracker, SMI Glasses, and Tobii Glasses) have enabled the study of visual perception and visual behavior in natural environments. [38]

4. Eye Tracking With Eye Glasses

This master study is concerned with the negative effects of wearing corrective lenses while using eye trackers, and the correction of those negative effects.

The eye tracker technology studied is the video based real-time Pupil Center and Corneal Reflection method. With a user study, the wearing of eyeglasses is shown to cause 20 % greater errors in the accuracy of an eye tracker than when not wearing glasses. The error is shown to depend on where on the eye tracker viewing area the user is looking. The developed mathematical/physiological model for eyeglasses focuses on artifacts not possible to accommodate for with existing calibration methods, primarily varying combinations of viewing angles and head rotations. The main unknown in the presented model is the effective strength of the glasses. Automatic identification is discussed. The model presented here is general in nature and needs to be developed further in order to be a part of a specific application. [39]

5. Gaze Tracking System for User Wearing Glasses

The glasses usually produce noise. In order to overcome these problems, a new gaze tracking method was proposed. The research is novel in the following four ways:

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1. A new control device for the illuminator was constructed, which includes four illuminators that are positioned at the four corners of a monitor.
2. System automatically determines whether a user is wearing glasses or not in the initial stage by counting the number of white pixels in an image that is captured using the low exposure setting on the camera.
3. If it's determined that the user is wearing glasses, the four illuminators are turned on and off sequentially in order to obtain an image that has a minimal amount of noise due to reflections from the glasses. As a result, it is possible to avoid the reflections and accurately locate the pupil center and the positions of the four corneal specular reflections.
4. By turning off one of the four illuminators, only three corneal specular reflections exist in the captured image. Since the proposed gaze detection method requires four corneal specular reflections for calculating the gaze position, the unseen specular reflection position is estimated based on the parallelogram shape that is defined by the three specular reflection positions and the gaze position is calculated.

Through experiments with the data from 20 test subjects, researchers were able to confirm that the system was effective regardless of whether the test subject was wearing glasses or no. [40]

6. Assessing Visual Fields in Patients with Retinitis Pigmentosa Using a Novel Microperimeter with Eye Tracking: The MP-3

The MP-3 microperimeter appears to be useful to evaluate central visual function in RP eyes, exhibiting test-retest reproducibility that is equal to, or better than, that observed in HFA 10–2 visual fields. Further studies should be carried out, however, to determine why sensitivities recorded with MP-3 are significantly lower than those observed with HFA. In addition, MP-3 was associated with longer test duration, hence further efforts should be made to overcome this problem.

Used eye tracking device: MP-3 microperimeter [41]

7. Quantification of visual function assessment using remote eye tracking in children: validity and applicability

The measurement of orienting gaze responses to visual information with eye tracking enables a nonverbal characterization of oculomotor and visual performance in children. Such measurements provide observation-based results that are comparable to standard visual function assessments, and have the advantage of giving quantitative results. Using this approach additional to standard clinical visual assessments is promising for providing support and guidance to visually impaired children of all ages. Used eye tracking device: The ET set-up consisted of a 24-inch TFT monitor sampling at 60 Hz with incorporated infrared corneal reflection and pupil tracking (Tobii T60XL; Tobii Technology, Sweden). [42]

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8. What to expect from your remote eye-tracker when participants are unrestrained

Practical experience and previous research show, that eye-tracking data quality, e.g. the accuracy of the recorded gaze position and the amount of data loss, deteriorates (compared to well-trained participants in chinrests) when the participant is unrestrained and assumes a non-optimal pose in front of the eye-tracker. How then can researchers working with unrestrained participants choose an eye-tracker? Results of our tests have shown that eye-trackers may have significant trouble tracking participants in non-optimal conditions, even though the participants' eyes remain in the headbox. This finding underscores the importance of not only looking at the manufacturer's specifications when deciding which eye-tracker to buy for your experiment, but to also consider and, when possible, test the eye-tracker in the conditions in which your experiment will likely take place.

Used eye tracking devices: five popular remote eye-trackers from EyeTribe, SMI, SR Research, and Tobii in a series of tasks where participants took on non-optimal poses: Tobii Pro TX300, EyeLink 1000Plus, SMI REDn Scientific, the Tobii T60XL, EyeTribe. [43]

Gaze based screen magnification

In the context of adult education, many people with low visual acuity use screen magnification systems. These allow to magnify screen portions or the whole screen for simpler reading. This section introduces the concept of these systems with the aim to clarify the current state of the art and the potential issues that might emerge. Finally the idea to connect gaze-estimation and screen magnification will be elaborated.

Screen magnification

People with low visual acuity require a certain magnification in order to be able to perceive various detailed screen contents. Many operating systems come equipped with a magnifying application; alternatively there are applications that provide magnification with advanced features. The most relevant parameters when using a magnification tool are:

- Magnification level
- Anti-aliasing
- Size of magnified area (window or full screen magnification)
- Contrast enhancement
- Color inversion
- Crosshairs

The amount of magnification is strongly dependent on the screen resolution, size and the viewer's visual acuity. While the contents can be scaled at will, if you ignore aliasing effects, the field of vision of the viewer and the screen size play a limiting role. The scale amount is either given as percentage relative to the original content or as simple scale factor. A letter with 15 pixel could be rescaled to 60 pixel by applying a 4x scale factor.

When doing so, it is very likely that lines will become jagged. This effect is called aliasing. While sometimes this effect is desired in order to retain a crisp contrast on edges, it is also possible that text should be smoothened along the edges. Hence anti-aliasing techniques aim to reduce these effects. Most commercial solutions and some of the build in solutions offer this feature.

The tools do allow either fullscreen or windowed magnification. Fullscreen magnification takes a portion of the original screen contents scales it up and shows it on the full screen. In the windowed or boxed mode only the scaled content is shown inside a defined portion of the screen. The most common form is a rectangle, but the shape might also be a circle. The mouse or a text cursor serve as point of reference to center the magnified portion. In the windowed version it is possible to move the whole window along with the cursor or to leave it steady on a fixed location. It is e.g. possible to show the magnified portion on the top 10% of the screen allowing to move

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the mouse over text and show the magnified screen portions always at the same fixed position.

Besides the magnification, many tools allow contrast augmentation, color inversion and even color mapping. This is required whenever a person is more sensitive to certain colors or requires very high contrast. Sometimes the bright light of the screen irritates the eye and the inversion can reduce this effect.

In order to allow better visibility of the mouse cursor, the color and size can be changed, some tools allow to enable crosshairs. This allows to achieve a better tracking of the cursor's location on the screen. Especially because the crosshairs can extend over the whole screen if necessary. This feature is again very helpful for people with a reduced field of vision.

Goals

The aim of Opeye is to enhance the user experience when working with a computer. The frustration due to low visual acuity should be reduced. Allowing the person to focus on their work rather than on the control of an accessibility tool. This implies that the person can work at a rapid pace, while avoiding to get stuck because the focus is lost. To achieve this, we propose a gradual magnification lens that is controlled by the user's gaze.

The lens' appearance will depend on the required magnification. This lens will show a portion of the screen magnified and gradually fade over to the whole screen. The lens' position and hence the magnified portion of the screen is controlled with the user's gaze and not as otherwise common by the mouse cursor position. The idea is that even with low visual acuity you might still want to perceive the whole screen contents to get more context.

Classic magnification can omit screen elements, for example the location of a button could be hidden because the magnification window covers it, or in the case of fullscreen magnification, the button is simply off screen. Having a gradual blending lens would prevents this, if it is not configured to scale too much. The user will always see the whole screen, even if strongly distorted at the lens boundaries, this allows to give hints of shapes of the screen elements.

Especially novice users tend to be overwhelmed by using the mouse as a pointing device and magnification focusing controller at the same time. Doing this implicitly with the user's gaze will take the burden of the viewer and separate the mouse pointing functionality from the magnification control.

Implementation approach

The system is aimed to be open & portable. In this context, portable means that it should work on many different operating systems without additional dependencies on special hardware. A consumer grade webcam should suffice for our needs. Open stands for open source, the project source code will be published on a source code distribution platform under the open source license that will suit best.

The application can be split up into two stages. First we need to implement a working gaze-tracking method. We need the screen space coordinates of a user's view. Then the program must access the screen contents and draw our magnification glass on top. In the best case a simple post-processing shader that is very flexible will do the job. A shader is a program that processes an image in the computer's graphics processor (GPU).

Gaze estimation & tracking is the more complex part here. Particularly because we want the system to be as flexible as possible. Many libraries on the subject do exist but appeared in an initial evaluation to be very prone to the environmental influences. The development of a prototype gaze tracking using OpenCV face tracking and a neuronal network that interprets the eye's gaze was quite successful. If well enough trained and set up with a good network layer architecture, it was good enough to estimate screen space coordinates up to a precision approximatively 2cm (sitting ~50cm away. This has to be verified, is this enough for magnification?). The neuronal net was developed with the aid of dLib, but it is likely that any kind of deep learning library will be able to do the same job. In detail, the following are the processing steps in our proposed approach:

- Grab a frame from the webcam
- Find the 68 facial marker using OpenCV.
- Isolate the preferred eye. This must be adapted for users with visual impairments.
- Normalize the image and take the first derivative.
- Feed the pre-trained neural net with the image to estimate the screen space point.
- Use a calibration to adjust the results correctly.

The approach is not very sensitive to the lighting situation, as long ass the sun does not blind the camera or the light is far to dim, the system works. If the facial landmarks can be found, the neuronal network can estimate a point on the screen.

Evaluation

The two stages of the program can be evaluated separately. The neuronal network of the gaze-estimation must be trained with large sets of data. It must be able to deal with the visual effects of the visual impairments we aim to support. Hence a training set and a verification set must be gathered. They must be completely labeled with all the data that is required for the algorithm. In this case, this means: which eye should

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be used for the evaluation, where does the user look at, what is the camera setup etc. While learning is done on the first set (usually 80% of the data) verification can be done on the other set. The summed differences between the actual gazed at point and the evaluated point serve as a suitable metric. Visual impairments should be used as amplifying factors. That same data for training and verification are used throughout the development. This asserts that changes to the algorithm lead to real improvements in the precision of the estimation. Systematically different network layers and image filters can be evaluated to evaluate which suits best.

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