WhitePaper

Tobii® Technology

# Tobii Eye Tracking

## An introduction to eye tracking and Tobii Eye Trackers

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January 27, 2010
Tobii Technology AB

Eye tracking commonly refers to the technique used to record and measure eye movements. In the last two to three decades we have witnessed a rapid evolution in eye tracking technology with systems becoming easier to operate and less intrusive to the test subjects. As a consequence the user base has also expanded with eye tracking being used more commonly in different research and commercial projects. The aim of this paper is to give a brief introduction to the human visual system, and to explain how eye movements are recorded and processed by Tobii Eye Trackers. Some basic concepts and issues related to remote eye tracking and eye movement data interpretation are also briefly discussed.

File version: Tobii_Whitepaper_TobiiEyeTrackingWhitepaper_270110.pdf

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# 1 Why study eye movements?

In order to understand the reasoning behind studying eye movements, some basic facts about the human vision need to be known. This section provides short explanations of important terms and characteristics of human vision.

## 1.1 How does the eye work?

Our eyes have many similarities with how a photo camera works: Light reflected from an object or a scene travels into our eyes through a lens. This lens concentrates and projects the light on to a light sensitive surface located on the back of a closed chamber. However, unlike a camera, the light sensitive surface (which in the eye is called the *retina,* see Figure 2) is not equally sensitive everywhere. Through evolution, our eyes have been designed to work in both dark and light environments as well as providing both detail and quick changes in what we see. This has led to certain compromises, e.g., that we can only see details clearly in a limited part of our visual field (in the eye called the *foveal area*). The larger part of our visual field (the *peripheral area*) is better adapted to low light vision, and to detect movements and register contrasts between colors and shapes. The image produced by this area is blurry and less colorful. Between these two areas we find a region of transition called the *parafoveal* area, in which the image becomes gradually more blurry as we move from the fovea into the peripheral area (see Figure 1).

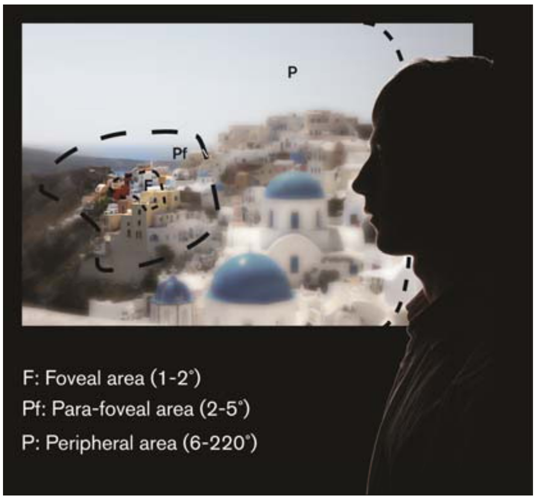


*Figure 1 The human visual field*
*This figure is a schematic representation of the human visual field. The main area that is in focus, F, corresponds to the area where we direct our gaze to – the foveal area. As is illustrated in this image, the foveal area is not circular. Hence, the area in focus will have a slightly irregular shape as well. Within the rest of the visual field (the para-foveal and peripheral areas) the image we perceive is blurry and thus harder to interpret and discriminate in high detail.*

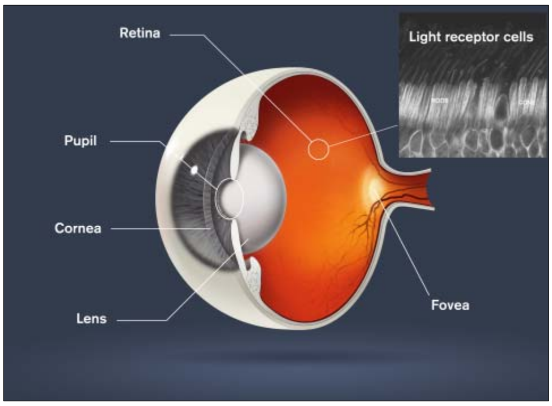


*Figure 2 The human eye*
*The retina is a light sensitive structure inside of the eye responsible for transforming light into signals, which are later converted into an image by the visual cortex in the brain. The fovea is a section of the retina that contains a high density of both kinds of light receptor cells found in the eye, i.e. Cone and Rod cells. Rod cells, which are mostly located in the outer retina, have low spatial resolution, support vision in low light conditions, do not discriminate colors, are sensitive to object movement and are responsible for the peripheral vision. Cone cells, which are densely packed within the central visual field, function best in bright light, process acute images and discriminate colors.*

The cause of the differences in our visual field is the two different kinds of light receptor cells available in the eye, i.e. the *rods* and the *cone* cells. About 94% of the receptor cells in the eye are rods. As mentioned previously, the peripheral area of the retina is not very good at registering color and providing a sharp image of the world. This is because this area is mostly covered by rods. Rods do not require much light in order to work, but do, on the other hand, only provide a blurred and colorless image of our surroundings. For more detailed and clear vision, our eyes are also equipped with light receptor cells called cones which make up about 6% of the total number of light receptor cells in our eyes. Cones are, in the human eye, most often available in three different varieties; one that registers blue colors, one that registers green and one that registers red. While being efficient in providing a clear picture, the cones do require much more light in order to function. Hence, when we look at things when it's dark around us, we lose the ability to see color and use mainly information registered by rods, providing us with a grey scale image. Cones are mostly found within the fovea where they are tightly packed in order to provide as clear an image as possible.

## 1.2 Why do our eyes move?

The human visual field spans about 220 degrees and is, as previously mentioned, divided in 3 main regions: foveal, parafoveal, and peripheral region. We primarily register visual data through the foveal region (Figure 1 and Figure 2) which constitutes less than 8% of the visual field. Even though this represents only a small part of our field of vision, the information registered through the foveal region constitutes 50% of what is sent to the brain through our optic nerve. Our peripheral vision has a very poor acuity, which is illustrated in Figure 1, and is only good for picking up movements and contrasts. Thus when we move our eyes to focus on a specific region of an image or object, we are essentially placing the foveal region of the eye on top of the area which is currently within main focus of the lens in our eye. This means that we are consequently maximizing our visual processing resources on that particular area of the visual field which also has the best image due to the optic characteristics of the eye. By letting the foveal region register the image, the brain get the highest resolution possible for the image of the interesting area to process as well as the most amount of data registered by the eye about that area. Hence, the brain is able to present the best possible image of the area we find interesting to us.

Eye movements have 3 main functions which are considered important when we process visual information:

1. Place the information that interests us on the fovea. To do this, *fixations* and *saccades* are used. A *fixation* is the pause of the eye movement on a specific area of the visual field; and *saccades* the rapid movements between fixations.
2. Keep the image stationary on the retina in spite of movements of the object or one's head. This movement is commonly called a *smooth pursuit*.
3. Prevent stationary objects from fading perceptually. Movements used for this are called *microsaccades, tremors* and *drift*.

**What are Visual Angles?**

Often when we read articles on human vision and eye tracking accuracy, we come across measurements expressed in visual angle, e.g. the size of the foveal area is estimated to be 1-2° visual angle, or remote eye trackers have an accuracy between 1-0.5°. (Note: A smaller angle means less inaccuracy.) When we point a flashlight on a wall in a dark room we can observe that the light forms a projection on the wall. The size and shape of this projection is related to the size of the light source and the distance that you stand from the wall. The reason the distance affects the size of the projection is because the light disperses at a specific angle from the source. Hence, if we wish to specify the size of the projection area using a standard size measure (e.g. cm or $cm^2$) of that flashlight we would always have to specify the distance at which it was measured. However, if we use the angle of dispersion as size indicator we can easily calculate the projection size for multiple distances using simple trigonometry. The same rationality applies to our visual field as images are formed through the projection of light on the retina, i.e. our eye works as a reversed flashlight that absorbs light instead of emitting it.

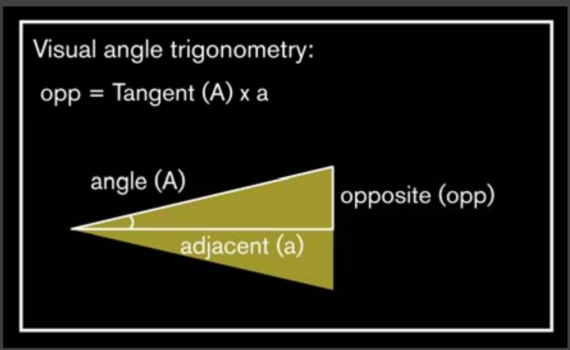


*Figure 3 Scene perception*
*Rather than perceiving an object or a scene as a whole we fixate on relevant features that attract our visual attention, and construct the scene in our visual cortex using the information acquired during those fixations.*

## 1.3 What is visual attention?

Whenever we look at the world, we consciously or unconsciously focus only on a fraction of the total information that we could potentially process, in other words we perform a perceptual selection process called attention. Visually this is most commonly done by moving our eyes from one place of the visual field to another; this process is often referred to as a change in overt attention – our gaze follows our attention shift. Even though we prefer to move our eyes to shift our attention, we are also capable to move our mind's attention to the peripheral areas of our visual field without eye movements (see Figure 1). This mechanism is called covert attention. Although we can use these two mechanisms separately they most frequently occur together. An example is when we are looking at a city landscape and we first use our covert attention to detect a shape or movement in our visual field that appears to be interesting and use our peripheral vision to roughly identify what it is. We then direct our gaze to that location allowing our brain to access more detailed information. Thus a shift of our overall attention is commonly initiated by our covert attention quickly followed by a shift of our overt attention and the corresponding eye movements.

## 1.4 How fast is human visual perception?

In addition to only having a very limited sharp field of vision, our eyes are also fairly slow at registering changes in images compared to the update frequency of a modern computer screen. Research has shown that the retina needs about 80 ms of seeing a new image before that image is registered in normal light conditions. This doesn't mean that we consciously have noticed any changes – only that the eye has registered a change. The ability to register an image is also dependent on the light intensity of that image. This can be compared with a photographic camera where a short shutter speed, in a badly lit environment results in a dark and blurred image, where hardly anything can be seen. However, if taking an image of something which is very well lit, e.g. a window, the shutter speed can be very short without this problem occurring. In addition to needing time to register an image, the eye also requires time for the image to disappear from the retina. This is also dependent on the light intensity. One example of this is when being exposed to a very bright light such as a camera flash where the image of the flash stays on the retina long after the flashing has ended.

In addition to the light sensitivity of the eye, how fast we perceive something we are looking at also depends on *what* we are observing. When reading in normal light conditions, it has been observed that most people only need between 50-60 ms of seeing a word in order to perceive it. However, when looking at, e.g., a picture people need to see it for more than 150 ms before being able to interpret what they are seeing.

### 1.5 What do we study when we use eye tracking data?

Most eye tracking studies aim to identify and analyze patterns of visual attention of individuals when performing specific tasks (e.g. reading, searching, scanning an image, driving, etc.). In these studies eye movements are typically analyzed in terms of fixations and saccades. During each saccade visual acuity is suppressed and, as a result, we are unable to see at all. We perceive the world visually only through fixations. The brain virtually integrates the visual images that we acquire through successive fixations into a visual scene or object (see Figure 3). Furthermore we are only able to combine features into an accurate perception when we fixate and focus our attention on them. The more complicated, confusing or interesting those features are the longer we need to process them and, consequently, more time is spent fixating on them. In most cases we can only perceive and interpret something clearly when we fixate on an object or are very close to it. This eye–mind relationship is what makes it possible to use eye movement measurements to tell something about human behavior.

## 2 How do Tobii Eye Trackers work?

The process of eye tracking is, from a technical point of view, divided into two different parts: registering the eye movements and presenting them to the user in a meaningful way. While the eye tracker records the eye movements sample by sample, the software running on the computer is responsible for interpreting the fixations within the data. This chapter is about what happens during an eye tracking process from a technical point of view and aims to answer a few of the questions that arise regarding this.

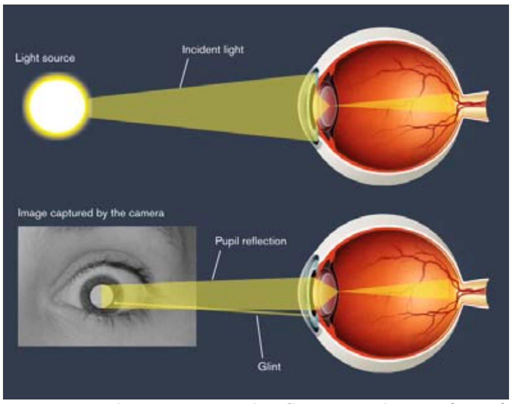


***Figure 4 Pupil Centre Corneal Reflection technique (PCCR)***
*A light source is used to cause reflection patterns on the cornea and pupil of the test person. A camera will then be used to capture an image of the eye. The direction of the gaze is then calculated using the angles and distances*

### 2.1 How are the eye movements tracked?

Eye tracking has long been known and used as a method to study the visual attention of individuals. There are several different techniques to detect and track the movements of the eyes. However, when it comes to remote, non-intrusive, eye tracking the most commonly used technique is Pupil Centre Corneal Reflection (PCCR). The basic concept is to use a light source to illuminate the eye causing highly visible reflections, and a camera to capture an image of the eye showing these reflections. The image captured by the camera is then used to identify the reflection of the light source on the cornea (glint) and in the pupil (See figure 4). We are then able to calculate a vector formed by the angle between the cornea and pupil reflections – the direction of this vector, combined with other geometrical features of the reflections, will then be used to calculate the gaze direction. The Tobii Eye Trackers are an improved version of the traditional PCCR remote eye tracking technology (US Patent US7,572,008). Near infrared illumination is used to create the reflection patterns on the cornea and pupil of the eye of a user and two image sensors are used to capture images of the eyes and the reflection patterns. Advanced image processing algorithms and a physiological 3D model of the eye are then used to estimate the position of the eye in space and the point of gaze with high accuracy.

## 2.2 What are Dark and Bright Pupil eye tracking?

There are two different illumination setups that can be used with PCCR eye tracking: bright pupil eye tracking, where an illuminator is placed close to the optical axis of the imaging device, which causes the pupil to appear lit up (this is the same phenomenon that causes red eyes in photos); and dark pupil eye tracking where the illuminator is placed away from the optical axis causing the pupil to appear darker than the iris.

There are different factors that can affect the pupil detection during remote eye tracking when using each one of these two techniques. For example, when using the bright pupil method, factors that affect the size of the pupil, such as age and environmental light, may have an impact on trackability of the eye. Ethnicity is also another factor that affects the bright/dark pupil response: For Hispanics and Caucasians the bright pupil method works very well. However, the method has proven to be less suitable when eye tracking Asians for whom the dark pupil method provides better trackability.

Tobii Eye Trackers of the T/X Series use both bright and dark pupil methods to calculate the gaze position while the earlier 50-series only used dark pupil eye tracking. Hence, the Tobii T/X Series Eye Trackers are able to deal with larger variations in experimental conditions and ethnicity than an eye tracker using only one of the techniques described above. All participants are initially subjected to both the bright and dark pupil methods and the method that is found to provide the highest accuracy is chosen for the actual testing. During a recording the Tobii TX-Series Eye Trackers do not change between bright and dark pupil tracking unless conditions change in a way that have a significantly negative impact on trackability. If that happens, the Tobii Eye Trackers conduct a new test where both methods are used simultaneously in order to determine which method is the most suitable for the new conditions and continue the recording using only the selected method.

## 2.3 What happens during the calibration?

Before an eye tracking recording is started, the user is taken through a calibration procedure. During this procedure, the eye tracker measures characteristics of the user's eyes and uses them together with an internal, physiological 3D eye model to calculate the gaze data. This model includes information about shapes, light refraction and reflection properties of the different parts of the eyes (e.g. cornea, placement of the fovea, etc.). During the calibration the user is asked to look at specific points on the screen, also known as calibration dots. During this period several images of the eyes are collected and analyzed. The resulting information is then integrated in the eye model and the gaze point for each image sample is calculated. When the procedure is finished the quality of the calibration is illustrated by green lines of varying length. The length of each line represents the offset between each sampled gaze point and the center of the calibration dot.

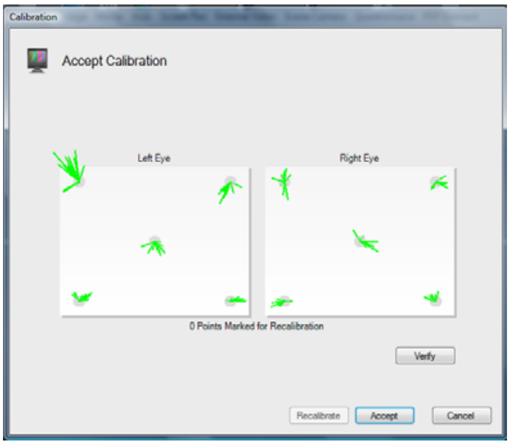


***Figure 5 Calibration results***
*Each collected data point is compared against the point on the screen the user was asked to looked at. The lines show the offset between the points and respective the gaze points.*

Large offsets (long green lines, Figure 5) can be caused by various factors such as, the user not actually focusing on the point, the user being distracted during the calibration or the eye tracker not being set up correctly. However, the user does not have to keep the head completely still during calibration as long as the focus of the user's eyes is kept on the moving dots. During the calibration both the light and dark pupil methods are tested to identify the most suitable for the current light conditions and the user's eye characteristics.

## 2.4 How are fixations defined when analyzing eye tracking data?

During a recording the Tobii T/X Series Eye Trackers collect raw eye movement data points every 16.6 or 8.3 ms (depending whether the sampling data rate is 60Hz or 120Hz). Each data point will be identified by a timestamp and "x,y" coordinates, and sent to the analysis application (e.g. Tobii Studio or an application using the Tobii SDK APIs) database running on the computer connected to the eye tracker. In order to visualize the data these coordinates will then be processed further into fixations and overlaid on a video recording of the stimuli used in the test.

By aggregating data points into fixations the amount of eye tracking data to process is reduced significantly. Tobii Studio uses two types of fixation filters to group the raw data into fixations. These filters are composed of algorithms that calculate whether raw data points belong to the same fixation or not. The basic idea behind these algorithms is that if two gaze points are within a pre-defined minimum distance from each other then they should be allocated to the same fixation – in other words the user has not moved the eyes between the two sampling points. In the Clear View fixation filter it is also possible to set a time limit to the minimum length of a fixation. Another function of the filters is to check if the sample points are valid, e.g. discarding the points with no eye position data or where the system has only recorded one eye and failed to identify whether it is the left or the right eye and is unable to estimate the final gaze point.

Graphically fixations are typically represented by dots (larger dots indicate a longer fixation time), whereas saccades are indicated by lines between fixations. A screen shot showing all the fixations a person made on a specific image or webpage is typically called a gaze plot (see Figure 6). Another popular way to visualize eye tracking data is through a heat map (see Figure 7). A heat map uses different colors to show the amount of fixations participants made in certain areas of the image or for how long they fixated within that area. Red usually indicates a highest number of fixations or the longest time and green the least, with varying levels in between. An area with no color on a heat map signifies that the participants did not fixate in the area. This does not necessarily mean they did not 'see' anything in there, but if it was detected it may have been in their peripheral vision, which means that it was more blurred.


*Figure 6 Gaze Plot or Scanpath image*
*The Gaze Plot visualization shows the movement sequence and position of fixations (dots) and saccades (lines) on the observed image or visual scene. The size of the dots indicates the fixation duration whereas the number in the dots represents the order of the fixation. Gaze Plots can be used to illustrate the gaze activity of a single test participant over the whole eye tracking session, or several participants in a short time interval.*

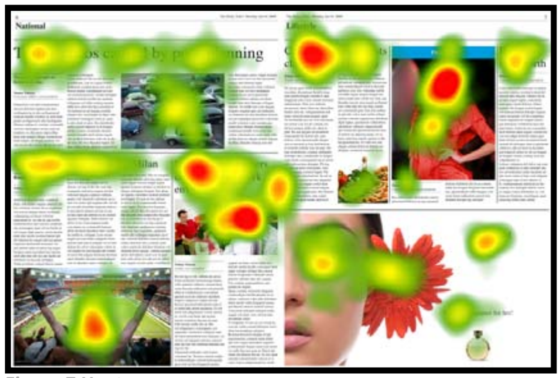

*Figure 7 Heatmap*
*The Heatmap visualization highlights the areas of the image where the participants fixated. Warm colors indicate areas where the participants either fixated for a long time or at many occasions. Heatmaps can be used to illustrate the combined gaze activity of several participants on an image or webpage*

## 2.5 Is pupil size calculation possible with Tobii Eye Trackers?

Knowing the size of the pupil and whether it changes over time is often used when studying emotional responses to stimuli. The eye model used by Tobii Eye Trackers allows for calculations of the position of the eyes as well as the pupil size. The optical sensor registers an image of the eyes which then is used to calculate the eye model. As the eye model used by Tobii Eye Trackers provides data about the distance between the eye and the sensor, the firmware can calculate the pupil size by measuring the diameter of the pupil on the image and multiply it with a scaling factor.

Several definitions exist regarding what should be defined as the size of the pupil. In the eye model used by Tobii Eye Trackers the pupil size is defined as the actual, external physical size of the pupil. However, in most scientific research the actual size of the pupil is less important than its variations in size over time. The T/X series Eye Trackers outputs pupil size information for each eye together with each gaze point allowing an external software (e.g. Tobii Studio) to record the pupil size variation during an eye tracking session.

## 2.6 How does blinking affect eye tracking?

Blinking is most often an involuntary act of shutting and opening the eyelids. During each blink the eyelid blocks the pupil and cornea from the illuminator resulting in raw data points missing the x,y coordinates information. During analysis fixation filters can be used to remove these points and extrapolate the data correctly into fixations.

Provided that the head movements are within the eye tracker specifications, i.e. that the missing data points do not originate from moving the head away from the eye tracking box[1], it is also possible to extract information on blinks from the raw data collected by the eye tracker. This can be done by extracting it manually from the raw data exported from Tobii Studio.

[1] An 'eye tracking box' is the area in front of an eye tracker within which the user can move without the eye tracker losing the ability to track the eyes. Tobii Eye Trackers have different eye tracking boxes dependent on model: For trackers running in 60 Hz the box measures about W:44cm x H:22 cm at 70 cm from the eye tracker and for 120 Hz eye trackers W:30 x H:22 cm at 70 cm distance from the eye tracker.

## 2.7 Does head movement affect eye tracking results?

During an eye tracking session head movements within the eye tracking box have very little impact on the gaze data accuracy. The optical sensor of the Tobii Eye Trackers is composed of two cameras that capture an image of the eyes at a given frequency (60 Hz or 120 Hz). The two cameras produce two images of the eyes simultaneously and the respective pupil and corneal reflections providing the eye tracker with two different sources of information regarding the eye position. This type of "stereo data processing" offers a robust calculation of the position of the eye in space and the point of gaze even if the position of the head changes.

Additionally the Physiological 3D Eye Model of each participant's eye offers an accurate and more robust way to determine the position of the eye and point of gaze of the participant independent of head movement.

# 3 What influences the accuracy of a Tobii Eye Tracker?

There are several factors that can affect the accuracy of eye tracking results; among them are eye movements, the calibration procedure, drift and ambient light. Eye trackers such as Tobii Eye Trackers can record saccades and fixations, pupil size and other useful data with a high accuracy.

## 3.1 Eye movements

As mentioned at the start of this white paper we perceive images or scenes by moving our eyes and fixating on areas of interest and that during each fixation we are essentially placing our fovea on the area or feature we wish to extract more detail about. The size of the fovea varies between 1-2° of the visual field meaning that if we stand at a certain distance from an object, the area covered by the fovea will be a projection of the size of the fovea in a 1-2° degree angle (see Figure 8 on the next page). When we move the fovea in order to place it on areas we are interested in we do not need to place it exactly centered and on top of the area as the projected area becomes larger and hence, covers more, the further away an object is.

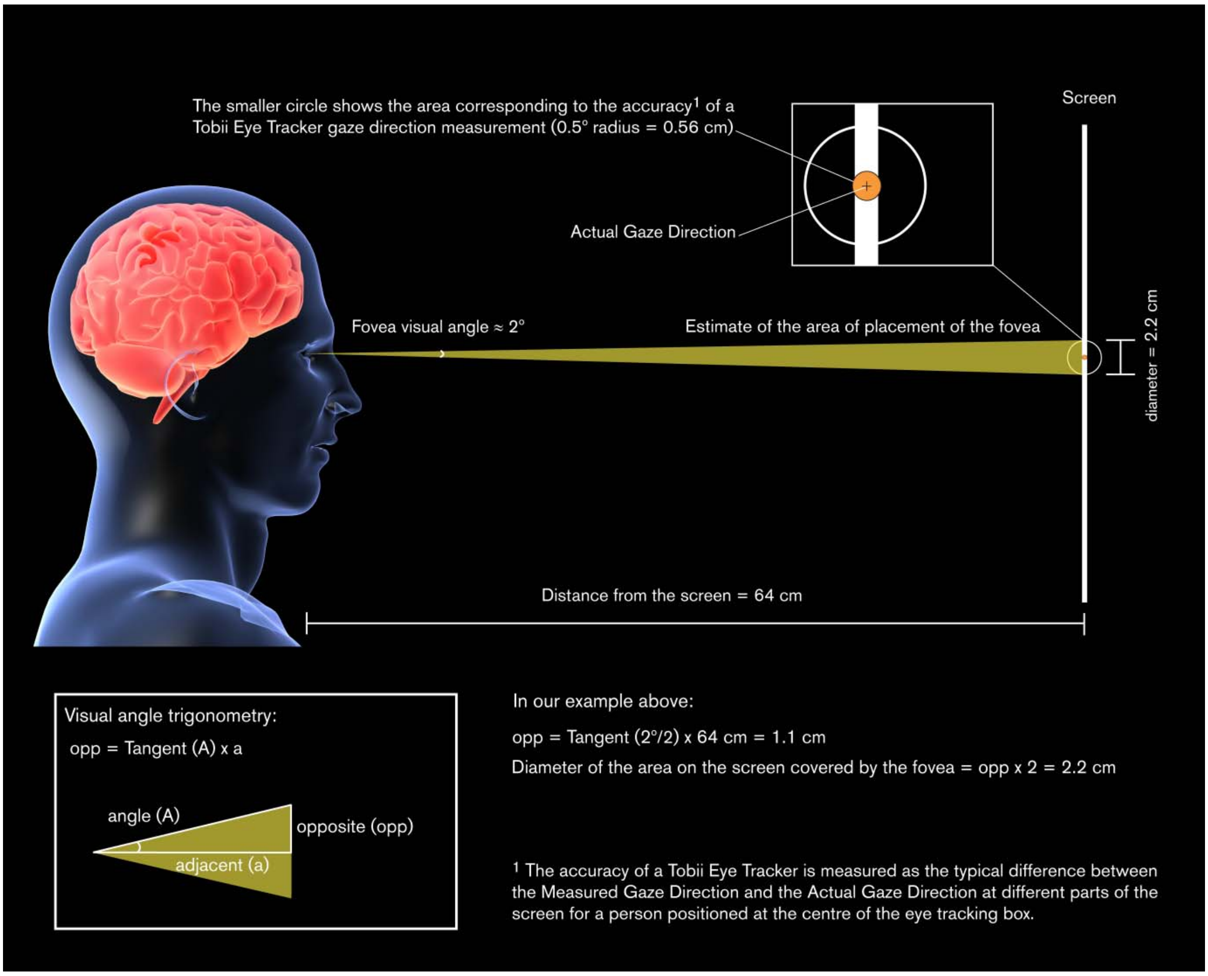


***Figure 8 Calculating the size of the visual angle on a screen.***
*In this example we assume that the fovea is approximately 2°of visual angle and we want to measure the corresponding size of the fovea on the screen when standing at the distance of 64. To calculate the size of the projection we can use basic trigonometry (see information box on the figure): first we need to assume that we can divide the projection of the fovea into two equal right angled triangles (mirroring each other). Thus the angle that we will use in the formula will be equal to the visual angle divided by 2. Secondly we measure the distance to the screen. We will use that value as the measurement of the hypotenuse of the triangle (adjacent side). Thirdly, we apply the two values (angle/2 and the distance to the screen) to the formula and obtain the measure for the shortest side of the triangle (opposite side). Finally, to obtain the value for the size of the projection of the visual angle on the screen we multiply the value for the shortest side of the triangle by two.*

In fact it is quite common that the fovea overlaps partially on the area and that this is enough to extract the level of detail we need, in particular if we are looking at a familiar scene or image. In addition, humans are generally unable to voluntarily direct their eyes to very precise locations for a long period of time. During steady fixations the human eye is in constant motion; small involuntary movements are triggered to avoid perceptual fading (overstimulation of the light receptors that causes the neurons to cease to respond to the stimulus). Thus, even if we perceive that we are looking at a specific spot on a scene our eyes are actually moving between different locations around the spot. Even though the accuracy of eye tracking results are influenced by human vision accuracy limitations, this influence only surfaces when doing very fine grained accurate studies. An eye tracker can record and replay what people are looking at within less than a centimeter's accuracy when measuring the point of gaze on a surface or screen under normal test conditions.

## 3.2 Drift

Drift is the gradual decrease in accuracy of the eye tracking data compared to the true eye position. Drift can be caused by different factors, such as variations in eye physiology (e.g. degree of wetness, tears) and variations in the environment (e.g. sunlight variations). However, drift problems only have a significant effect if the test conditions change radically or if the eye tracking session is long. In these cases it can be attenuated by recalibrating frequently. Today, many eye trackers (including the Tobii T/X series) are able to cope well with drift, however extreme changes in the eye physiology during an eye tracking session can still produce a significant drift effect.

## 4 What does eye tracking data tell us?

Eye tracking analysis is based on the important assumption that there is a relationship between fixations, our gaze and what we are thinking about. However, there are a few factors that need to be considered for this assumption to be true which will be discussed below.

First, sometimes fixations do not necessarily translate into a conscious cognitive process. For example, during a search task one can easily fixate briefly on the search object and miss its presence, especially if the object has an unexpected shape or size (commonly called *change blindness*). This happens because our expectation of what the object (or scene) should look like modulates our visual attention and interferes with the object detection. This effect can be eliminated from a test if you give clear instructions to the participant, and/or follow up the eye tracking test with an interview to assess the participant's motivations or expectations.

Second, fixations can be interpreted in different ways depending on the context and objective of the study. For example, if you instruct a participant to freely browse a website (encoding task), a higher number of fixations on an area of the webpage may indicate that the participant is interested in that area (e.g. a photograph or a headline) or that the target area is complex and hard to encode. However, if you give the participant a specific search task (e.g. buy a book on Amazon), a higher number of fixations are often indicative of confusion and uncertainty in recognizing the elements necessary to complete the task. Again, a clear understanding of the objective of the study and careful planning of the tests are important for the interpretation of the eye tracking results.

And third, during the processing of a visual scene, individuals will move their eyes to relevant features in that scene. Some of these features are primarily detected by the peripheral area of our visual field. Due to the low acuity, a feature located in this area will lack shape or color detail but we are still able to use it to recognize well-known structures and forms as well as make quick, general shape comparisons. As a result, we are able to use the peripheral vision to filter features according to their relevance to us, for example, if we generally avoid advertisement banners on webpages, we might also avoid moving our eyes to other sections of the webpage that have a similar shape simply due to the fact that our peripheral vision "tells" us that they might be banners. The current eye tracker technology will only show the areas on the visual scene that the test subject has been fixating at and the jumps between them (i.e. not the whole visual field). Thus, to fully understand why a test person has been fixating on some areas and ignoring others, it is important that the tests should be accompanied by some form of interview or think-aloud protocols.

## 5 Conclusion

Eye tracking is an important technique that offers an objective way to see where in a scene a person's visual attention is located. However, as with any other analytical technique, it is necessary to have a clear methodology that is adequate to the context and objectives of the study if we wish to understand and interpret the eye tracking data correctly.

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