Are high-end and webcam eye trackers comparable?

Timo Anthonijsz – 6642268

July 2 2021

t.h.j.anthonijsz@students.uu.nl

Abstract

Eye Tracking has seen a lot of developments in the last decade. With the introduction of a pandemic and high-end eye trackers being very costly there has been a surge of webcam eye trackers. In this paper, a literature overview of some high-end eye trackers and webcam eye trackers is created, as a review similar to this does not exist yet. Starting off, a list of eye trackers was made and after a filtering process, 10 eye trackers were selected for this overview. Each of these eye trackers were displayed within their own context. This showed that eye tracking is being used for many different purposes. High-end eye trackers and webcam eye trackers each have their own areas in which they perform better. The overview created in this paper provides a helpful guideline for the selecting of an eye tracker within a research context. In this paper, we criticize the results provided in webcam eye tracker papers, as they do not provide sufficient information to back up their results. This paper is finalized by recommending that future research could add an evaluation of testing results from the different eye tracker software.

Thesis for obtaining the bachelor degree in Artificial Intelligence

Utrecht University

Supervisor: Alex Hoogerbrugge

Second Examiner: Jakub Dotlacil

Contents

1. Introduction ... 2
1.1 Eye movements ... 3
1.2 Precision & Accuracy ... 3
1.3 Visual Angle ... 3
1.4 How does an eye tracker work? ... 4
1.5 Differences between webcams and eye trackers ... 4
2. Method ... 4
2.1 Gathering process ... 5
2.2 Analysis method ... 5
2.3 Selection process ... 5
2.4 Comparing Process ... 5
3. Results ... 5
3.1 Dedicated hardware eye trackers ... 5
3.2 Software Eye trackers ... 6
4. Comparison ... 8
4.1 Usability ... 8
4.2 Functionality ... 9
4.3 Reliability ... 9
5. Discussion ... 10
6. Conclusion ... 10
7. References ... 10

1. Introduction

Eye tracking is a research method that has been around for a while. Eyelink, which is one of the bigger companies in the eye tracking world posts a graph each year showing the number of publications for that year. This graph shows that eye tracking has become increasingly popular over the last decade, with more publications on eye tracking each year (Hutton, et al., 2020). Eye tracking is a process in which movements of the eyes are tracked to determine where a person is looking. Eye tracking can be implemented in a lot of different areas. For instance, in a human-computer interaction background eye tracking is used to examine visual attention during website exploration (Wang, 2014). In the medical field, eye tracking is used to support the diagnosis of mental diseases, such as schizophrenia (Kim, 2018). In psychological studies, eye movements are tracked during reading tasks to find patterns or characteristics (Rayner, 1998). The ways in which eye tracking can be used will only increase if eye tracking becomes a more accessible technology.

Big eye tracking companies (Tobii, Eyelink) have been the leaders in eye tracking research for a long time. The biggest problem for most researchers is that the eye trackers from popular companies are very expensive. A cheaper or free alternative could be more attractive. The current pandemic has created numerous difficulties for eye tracking experiments at the lab. Extra safety regulations have been set in place and recruiting participants has become increasingly difficult. Because of these reasons remote eye tracking has become a more popular alternative.

According to Majaranta and Bulling (2014) there is a growing interest in pervasive attention-aware systems, which could bring mainstream human-technology to the next level. Eye tracking could become one of the mainstream technologies. Due to technical developments in the camera and smartphone industry, cameras have become available to almost everyone. Nowadays, almost every mobile device has a camera. This has opened up new possibilities within eye tracking including webcam eye tracking or phone eye tracking. Several research teams and companies have introduced these new types of eye tracking. A similar goal is shared between these people, eye tracking should become more accessible. It needs to be implemented in such a way that webcams or even mobile phones can effectively use this technology.

The goal of this paper is to compare several eye trackers that are currently available. This will include high-end eye trackers and webcam eye trackers. First of all a list of eye trackers needs to be created. The process of gathering the eye trackers is part of this paper as well. To be able to make a sufficient comparison some sub-questions will be answered in this paper. Setting apart the small differences between the similarities in the eye trackers will be significant to obtain a correct comparison.

A decade ago, it would not have been possible to efficiently use webcam eye tracking. The introduction of JavaScript libraries for eye tracking has made webcam eye tracking feasible (Semmelmann, Weigelt, 2018). During the last decade, eye tracker technology has been implemented in even more programming languages including C++, C#, and Python. The webcam eye trackers are still relatively new and a overview does not exist yet. This paper is relevant to support choosing the right eye tracker for the right purpose and should provide insight for those interested in these upcoming eye trackers.

This paper has been divided into five parts. The first part consists of the main goal and a theoretical background, which should form the baseline on which this comparison will be built. The second part is divided into two subsections, firstly the gathering of the eye trackers. Secondly the selection of the eye trackers, which will result in a final list of eye trackers. In the third part, the eye trackers will be highlighted on their own. The fourth section presents the findings of the research, which will be displayed as the comparison between the eye trackers. The last section consists of a discussion and a conclusion finalizing the paper.

1.1 Eye movements

The most important eye movements for this paper will be highlighted in this part. The most basic eye movements are fixations and saccades. A fixation is a moment in which the eyes stay fairly still. During fixation a person gathers the information available in their field of view. Average fixation times are between 200-300 milliseconds, but these are simply the averages. Some fixations will only take less than 100 milliseconds while others might take 500 milliseconds, this all depends on the task at hand (Rayner, 2009). Saccades are small movements that happen in between fixations. Saccades last around 30ms, but just as with fixations, this can differ a lot based on the type of task the eyes are executing. With the given fact that some eye movements only last a very short time and eye movements only cover a very small distance, an eye tracker should be equipped with a camera that can reach enough frames per second to properly research the eye movement. As an example take an eye movement that lasts 50 milliseconds. A 20 frames per second camera is exactly enough to catch the complete movement, but the chance of doing this is very small. To actually research the complete eye movement the camera used should be able to catch more frames of the movement, which means it should have at least a multiplication of the frames per second to obtain useful data.

1.2 Precision & Accuracy

Precision and accuracy are the two main indicators of eye tracker data validity. Precision is defined as the ability to reproduce the same gaze point measurement. For instance if a person performed two movements that look exactly the same, an eye tracker with perfect precision would get two identical pieces of data. Precision measures the variation of the data using the Root Mean Square (RMS) of correct samples.

Accuracy is defined to measure the distance between the found location and the actual stimuli. The accuracy of an eye tracker is influenced by many factors and can vary depending on participant, illumination, calibration, etc. (Tobii Pro, 2015). The accuracy and precision of high-end eye trackers is always available in the product description, but most of the times this is a number that would only be correct during optimal circumstances. Webcam eye trackers do not always mention their accuracy or precision as consistently as high-end eye trackers. The precision of webcam eye trackers is left out in a portion of the papers. The accuracy of webcam eye trackers is sometimes provided in a different metric.

1.3 Visual Angle

Visual angle is one of the most important concepts within eye tracking research. It is used to describe the size of visual stimuli subtended at the eye. During research it might be important to ensure that the stimuli stay within the “trackable range” of their system. For instance a trackable range of 20 degrees of visual angle on the x-axis and 15 degrees of visual angle on the y-axis. The accuracy values of high-end eye trackers are usually reported in degrees of visual angle. For instance the Eyelink 1000 Plus is accurate to <0.5 degrees of visual angle. This value is calculated based on the distance away from the screen and the size of the object being viewed (Hutton, 2021). Calculating the Visual Angle for webcam eye trackers is harder, because most of the times both the distance from the screen and the size of the screen are unknown.

1.4 How does an eye tracker work?

An eye tracker records gaze location and eye motion to observe the visual attention of a person. High-end eye trackers are usually equipped with infrared lights. Some light is shone into the centre of the eye, the pupil. Because of this light, a reflection is produced in the pupil and cornea, which is the outermost transparent layer of the eye. Due to the increased contrast infrared lights provide, the borders of the pupil and the reflections can be detected in a more accurate way. Webcam eye trackers are usually not equipped with infrared lights, which makes it harder to achieve the same quality reflections (Farnsworth, 2019). The reflections are picked up by the eye tracker’s cameras and after putting the reflection data through an algorithm, the eye tracker can approximately figure out where you are looking. Webcam eye tracker must rely on the image produced by the webcam. This image is then similarl to high-end eye trackers analysed by an algorithm to determine the exact position a person is looking at. Before an eye tracker can correctly determine where you are looking it needs to be calibrated. A calibration process consists of a series of points that need to be looked at by the person using the eye tracker. After finishing the calibration process the results are validated to check whether the calibration was successful. Now the eye tracker is set up and ready to go. (Carter, Luke, 2020)

1.5 Differences between webcams and eye trackers

Webcams are not designed for eye tracking, while a high-end eye tracker is equipped with cameras specifically designed for the tracking of eyes. This leads to several limitations on webcams compared to eye tracker cameras. As already mentioned before, high-end eye trackers are usually equipped with infrared light, which helps with creating optimal conditions for retrieving reflection information of the eyes. It is uncommon for webcams to be equipped with infrared lights, so webcam eye tracker data relies on images recorded by the webcam.

Eye trackers have differing data acquisition speeds – this is called the sampling frequency. The sampling frequency of eye tracker cameras ranges from 30hz up to 2000hz. The sampling frequency determines the interval between each sample. For instance, a 60hz camera will make 60 eye samples in a second. Having higher sampling frequencies opens up the possibility of researching more characteristics of eye movements, such as micro saccades or other fixational movements. Webcams usually have a refresh rate between 30-60hz, which makes research into very small eye movements almost impossible. Recognizing the beginning and end of specific eye movements becomes very hard with these lower sampling frequency cameras. (Tobii Pro, 2016) This is one of the reasons why most webcam eye trackers focus mainly on gaze estimation and fixations of the eyes.

As webcams are way more accessible than high-end eye trackers, it is much easier to collect large-scale data once you have set up an experiment. Webcam eye trackers can compensate for the lack of accuracy and precision compared to more expensive eye trackers. Namely, having larger amounts of training data available will most of the time lead to a more versatile and better algorithm. A better algorithm could compensate for a portion of the benefits high-end eye trackers have over webcam eye trackers.

The price of a high-end eye tracker also plays a significant role. High-end eye trackers usually cost thousands of euros. This does mean they are usually used in a closed experimental setting. Setting up an experiment for a high-end tracker usually requires more time. Most of the time the experimental setting needs to be observed continuously, which is time consuming. Webcam eye tracking on the other hand, only needs a correctly set up experiment with clear instructions for the participants. This decreases the workload on the creator during the research process and creates the possibility of recruiting more participants.

From all these differences it should be clear that both types of eye trackers have usability in different types of research. High-end eye trackers will be more efficient in very specific and precise research concerning smaller eye movements. Webcam eye trackers will find more usage in research areas that require larger-scale data.

2. Method

In this section, the process of selecting and analysing the eye trackers is explained.

2.1 Gathering process

First of all, a list of eye trackers was created. This list has been created by searching for eye trackers, while still keeping all possible options for eye trackers open before selecting the eye trackers that seem most relevant. Tobii, Eyelink, Pupil Labs were the three most obvious additions to the list based on being well known and the amounts of papers that mention them. The online eye trackers were gathered after this. This process consisted of finding online eye trackers who were published with a dedicated paper and reading articles that gave a summary of some of the available online eye trackers at that moment. At the end of the process, the list consisted of 20 different eye trackers.

2.2 Analysis method

After the list of eye trackers is completed, each eye tracker will be put in a general category. The main 2 categories are dedicated hardware eye trackers and software eye trackers. The software eye trackers have been divided into their respective coding languages. Every eye tracker will receive a short explanation covering the following parts. (1) The developer of the eye tracker, (2) the usage of the eye tracker, (3) a reflection on how accurate the eye tracker is, (4) any innovative or very different approaches towards eye tracking in comparison to the other eye trackers. The most important information has been summarised in a table under the overview of the eye trackers.

2.3 Selection process

The only eye trackers that would certainly have a spot on the list are Tobii, Eyelink, Pupil Labs. The other 17 eye trackers have been narrowed down based on the following things. First of all, it was checked whether these online eye trackers were available for anyone. Eye trackers that seemed to have limited availability were removed from the list. Sticky a webcam eye tracker software made by Tobii, was removed, as it only provided a free demo. Secondly, it was made sure that each eye tracker came with enough information to create a comparison. During this second filtering step GazePointer (Ghani, et al., 2013) was removed. The functionality of this eye tracking software was too limited to compare it with other eye trackers. There should at least be a possibility to compare the eye trackers based on their performance. Lastly, the eye trackers should still be relevant. Any eye tracker that seemed outdated due to their limited support or appearance in other papers during the last decade were also removed. In this last step eye tracking software like Ogama (Voßkühler, et al., 2008) and OpenGazer (Nel, et al., 2012) were removed.

2.4 Comparing Process

This will be the last part of the results section and in this part eye trackers with similar goals will be compared. The eye trackers will be compared on different aspects, such as usability, functionality, reliability. Usability will tackle the difficulty of using the eye tracker. Functionality will cover the main usages for each of the eye trackers. Is the eye tracker multifunctional or does it serve a single purpose? Reliability will go in on how accurate the eye trackers are in comparison to one another.

3. Results

Each eye tracker from the final list will be highlighted in this part. The most important points are summarized in Table 1.

3.1 Dedicated hardware eye trackers

Since the high-end eye trackers are all companies with more than one product, the choice was made to only highlight one of the eye trackers from each company respectively. The selected eye trackers are serving as flagship products for their respective companies. In the case of Tobii the eye tracker chosen is their best eye tracker for research purposes.

Eyelink

As one of the biggest eye tracking companies Eyelink has a line of products and software. The Eyelink 1000 is one of the most popular eye trackers overall and this eye tracker will be used as a guideline during this study. This eye tracker is mainly used for research purposes and is usually mounted onto either a computer screen or an object. It is currently considered the best eye tracker on the market, due to the high precision and accuracy this eye tracker has. The Eyelink 1000 Plus can sample at 2000hz while the head is stabilized and up to 1000hz with free movement. Previous testing results have shown that the spatial accuracy averaged 0.57° (Ehinger, et al., 2019; Eyelink 1000 Plus, 2020).

Tobii

As the eye tracking company with the highest number of publications, Tobii is the company with the most versatile product line. Tobii sells eye trackers for research, but for instance for gaming as well. Research purpose eye trackers are the most interesting for this paper, so the Tobii Pro Spectrum will be the primary focus. It is a stationary screen-based system that can be mounted onto a screen, but can be used without a screen as well. It is designed for studying human behaviour and fast eye movements. As this eye tracker can cover a rather large area, it has a high tolerance for head movements, which increases the number of purposes it can be used for. With a maximum of 1200hz, it can detect very small movements. Tobii claims a 0.30° spatial accuracy in optimal conditions. According to Nyström, et al. (2021) the actual value of the spatial accuracy lies around 0.50° – 0.80° in most cases (Tobii Pro, 2016).

Pupil Labs

Focusing more on headwear for eye tracking Pupil Labs has created glasses for eye tracking, which is the item that will be looked at. Compared to the other two high-end eye trackers mentioned in this paper, Pupil Labs has taken a more mobile approach. The Pupil Core is worn just as any other glasses. As this product is quite mobile it does remove some of the movements restrictions the other high-end eye trackers have, as they are stationary machines. In comparison to the other 2 high-end eye trackers the coding behind Pupil Labs technology is open source. With only 200hz this eye tracker does have a significantly lower sampling frequency than the other two high-end eye trackers. After performance testing the spatial accuracy averaged on 0.82°(Ehinger, et al., 2019; Pupil Labs, 2020).

3.2 Software Eye trackers

3.2.1 JavaScript

WebGazer

Developed by the combined effort of researchers at Brown University and Pomona College in the United States of America, Webgazer is an open source eye tracker using webcams to track gaze locations of web visitors on a webpage. The calibration process of this eye tracker is rather unique. After the first 9 point calibration, WebGazer will continuously keep self-calibrating using information gathered from user interactions such as clicks or cursor movements. This eye tracker consists of two main parts. A pupil detector and a gaze estimator that uses regression analysis. This eye tracking library has been written in JavaScript and trains various models for estimating gaze during user interactions. WebGazer can be implemented in a webpage using JavaScript. The best performance of WebGazer concluded in an error of 104 pixels. The researchers obtained these results in a remote online setting. WebGazer can be used in settings where the approximation of gaze is the main research target (Papoutsaki, et al., 2016).

SearchGazer

Developed by a portion of the research team that developed WebGazer, SearchGazer is an open source eye tracker extending on WebGazer. SearchGazer is specifically focused on identifying areas of interest on search engines. Google and Bing are currently the only supported search engines. During the research, the performance of SearchGazer was evaluated comparing the predictions made by SearchGazer's regression model to true locations across 50 clicks. This evaluation resulted in an average distance between gaze locations and predictions of 128.9 pixels. This eye tracking software is not the most accurate, but the developers do mention that accuracy was not the main goal. SearchGazer aims to be a useful tool in a setting where the distribution of gaze locations is sought after and is used to create prediction heatmaps on search engine pages (Papoutsaki et al., 2017).

xLabs

XLabs has created JavaScript-based software designed to fit into a broad range of industries. Their three main industries include Market Research, e-Learning, online employee training. Compared to other free eye trackers the software if xLabs is not open source. Insight into the source code is only available for commercial partners. XLabs uses software that will continuously track where you are looking, while allowing some degree of free movement. It is used as an extension for web browsers. The browser extension provides replays of the recorded gaze viewing and can generate aggregate heatmaps based on the viewing patterns of users. XLabs tested their software in a large-scale experiment that covered over 1 million images. This resulted in a Gaze accuracy ranging from 15 mm (90pixels) distance for half of the predictions and up to 51 mm (300pixels) when including 95 percent of all predictions. XLabs claims the errors do not have a high correlation and claim that a great portion of the errors can be eliminated by using a filter. After applying this filter an average error of 29mm was found (XLabs Pty Ltd, 2014).

TurkerGaze
TurkerGaze is eye tracking software made by a research team at Princeton University in America. This eye tracker was designed to collect saliency data on a large scale. The code for this eye tracker is written in JavaScript. The researchers designed an experiment to collect saliency data within a web browser. These experiments were designed as two game-like interfaces. In these games the gaze of participants was shown on the screen as a crosshair and used to shoot appearing targets. Using the data gathered the researchers were able to create saliency maps on a set of natural images. The researchers tested the eye tracker against some of the high-end eye trackers and obtained the following results. A mean error of 0.33° just after calibration, going up to 1.06° median error after testing performance on a 33 point test (Xu, et al., 2015).

3.2.2 MATLAB

Gazecapture/ITracker
GazeCapture was created by a combined research team from the University of Georgia and the Massachusetts Institute of Technology. GazeCapture is the first large-scale dataset for eye tracking. Containing data from over 1450 people, consisting of 2.5 million frames. GazeCapture's data was collected by using an IOS app. This app also named GazeCapture, could record and upload gaze tracking data. This data was collected using a simple dot fixation task. With the dataset GazeCapture, a convolutional neural network(CNN) for eye tracking named ITracker was trained. ITracker uses inputs for both eyes, the face, and a face grid. After an image has passed through the CNN, the output will be the distance to the phone camera given in centimetres. After performing an eye tracking experiment in which gaze had to be predicted. ITracker achieved an error of 1.04 centimetre and 1.69 centimetre on mobiles and tablets respectively (Krafka, et al., 2016).

3.2.3 Python

GazeParser
GazeParser is an open source library for low-cost eye tracking and data analysis created by Hiroyuki Sogo. It is mainly used in an experimental setting and has been written in Python. Compared to the other free eye tracking solutions, this eye tracking library has been tested not by using a webcam, but using a 300 dollar OptiTrack V120 Slim camera, which is equipped with infrared lights. This will mean that results with any lower budget webcam or camera will differ by some amount. Sogo performed an experiment to test the performance of the eye tracking software. People had to look at squares randomly appearing on a screen. During the experiment the spatial error found was between 0.7° and 1.2°. Spatial error was defined as the mean distance between the target position and recorded gaze position (Sogo, 2013).

3.2.4 C#

ITU Gaze tracker
ITU Gaze tracker is a software created by the University of Copenhagen. The ITU Gaze Tracker is open source, but quite different in comparison to other free eye trackers because it has been developed to function with webcams with built-in infrared lights. This gaze tracking software is developed in C# and does require some technical knowledge to be set up. This eye tracker is mainly used to control the mouse cursor with your eyes and can be used in combination with a typing application to type with vision. Based on a usability test executed by a research team, a mean error of 59pixels was found for this eye tracker. (Johansen, et al., 2011; San Agustin, et al., 2010).

Eye Tracker	**Developer**	Cost(euros)	Citations	Reported accuracy	Sampling frequency	Main usage	Open Source
Eyelink 1000	Eyelink	10000+	15000+	0.57°	2000hz	Research	No

Tobii Pro Spectrum	Tobii	10000+	20000+	0.50-0.80°	1200hz	Research	No
Pupil labs Core	Pupil labs	2740+	3000+	0.82°	200hz	Research	Yes
WebGazer	Brown University/Ponoma College	Free	18	104 pixels	30-60hz	Webpage analyses	Yes
SearchGazer	Brown University/Ponoma College	Free	38	128.9 pixels	30-60hz	Search Engine analyses	Yes
xLabs	xLabs	Free	*	90-300 pixels	30-60hz	Continuous gaze tracking	Paywall
TurkerGaze	Princeton University	Free	138	1.06°	30-60hz	Saliency Prediction	Yes
ITracker	University of Georgia	Free	523	1.04cm and 1.69cm**	15-30hz	Phone/tablet eye tracking	Yes
GazeParser	Hiroyuki Sogo	Free	32	0.7-1.2°	Up to 500hz	Research	Yes
ITU Gaze Tracker	University of Copenhagen	Free	226	59 pixels	30hz	Gaze Tracking	Yes

Figure 1: This table displays some important information for each of the eye trackers.* The number of citations for Xlabs could not be found **Itracker's reported accuracy is respectively for mobile phones and tablets.

4. Comparison

To be able to compare the eye trackers they have been put into different groups. Some eye trackers had main purposes that did not align. Comparing eye trackers with completely different goals would not serve any purpose. The 1st group includes Eyelink, Tobii, and Pupil Labs. This is the high-end eye tracker group with a main purpose in psychological research. The 2nd group will include WebGazer, SearchGazer and xLabs. This group is more focused on eye movements during the visiting of web pages. The 3rd group consists of TurkerGaze, Itracker, GazeParser, ITU Gaze Tracker. This last group consists of eye trackers that used different techniques to create eye tracking software or obtain eye tracking data, like the neural network used to create the ITracker.

4.1 Usability

Group 1

The high-end eye trackers are usually only used by researchers during quite specific research. These eye trackers do require a considerable amount of background information, but the people using them are expected to be qualified to use these types of equipment. In comparison to the free eye trackers, there will be a substantial difference in supportability. The ability to ask for support is very much present for these high-end eye trackers. This is unfortunately not the case for a great deal of the free eye trackers, so even if you run into a problem there is a whole team from the company itself that can offer support.

Group 2

These three eye tracking software are all JavaScript-based and seem to have some sort of active support service. All three of these eye trackers have their web pages with instructions on how to install and use them. Search- and WebGazer are scripts that you add to a webpage. XLabs has made a browser extension, which can be added to your browser. This makes all three of them quite easy to use.

Group 3

The last group has more diverse difficulties in usability. The ITU Gaze tracker comes with its own program, which has a simple layout, with variable sliders for pupil detection. Choosing the right settings requires some technical knowledge. This eye tracker uses webcams with infrared lights. GazeParser is a Python module so some knowledge of Python is required. GazeParser still receives annual updates, so getting support might be possible. Similar to the ITU Gaze tracker, GazeParser does support infrared light cameras. TurkerGaze has specifically designed two game-like experiments, so using them is a possibility. Setting any sort of experiment up for yourself using the software of TurkerGaze does require knowledge of JavaScript. ITracker is eye tracker software designed for mobile devices IOS specifically. This software is quite outdated since Apple products progressed quite a lot during the last 5 years. This means tweaking the source code is probably necessary before making the ITracker functional on IOS once again.

4.2 Functionality

Group 1

The first group has the most research options, due to the quality of the eye trackers. These eye trackers have the highest sampling frequencies, which means many different eye movements can be researched. Tobii and Eyelink both offer additional equipment for mounting the eye tracker. From accurate saccade research to fixation-based research, these two eye trackers should be capable of performing the complete range of eye tracking studies. The Pupil Labs core allows for a freer research setup as it is a mobile device.

Group 2

WebGazer and SearchGazer will both run completely on the web browser, this means no data has to be sent to remote servers. WebGazer's main functionality is to infer eye gaze locations during a web page visit a webcam. SearchGazer only focuses on inferring gaze locations of visitors on a search engine in real-time. XLabs has more to offer than the other 2 eye trackers. It does continuously track gaze, but the software of xLabs sets itself apart during the analyses of the data. Their extension provides the user with instant replays and the ability to create aggregate vision heatmaps.

Group 3

The ITU Gaze tracker and GazeParser are the two webcam eye trackers that chose to implement infrared light supportability. This does mean that the quality of the obtained reflections will probably be better. Just as the name ITU Gaze tracker suggests, it is used for tracking gaze. GazeParser serves the same purpose, but with recording options and data analysis in Python. TurkerGaze used gaze tracking software to gather large-scale data. This data was used to create saliency prediction maps. Both the eye tracking software and the saliency map tool are open source and can be used. ITracker predicts gaze on mobile phones and tablets.

4.3 Reliability

Group 1

The three high-end eye trackers each have an accuracy < 1.0°. This means that in most experimental settings, in which the participant is 50-75 centimetres from the screen, the error of the eye tracker would be less than 1 centimetre. These eye trackers have been tested thoroughly, so there is no doubt that they are reliant.

Group 2

The three eye trackers in this group focus on web pages. As webpages usually have a pretty concise structure a centimetre error should not affect the effectiveness of the data as much. WebGazer reported a close to 2 centimetre error and SearchGazer reported a little over 2 centimetre error. Data gathered from these two eye trackers should be reliable enough for web page gaze tracking. XLabs on the other hand reports an average error of approximately 3 centimetre, on an average laptop screen, which is around 13 inches this would be an error of approximately 10% of the screen size.

Group 3

The ITU Gaze Tracker reported a mean error of 59 pixels, so approximately a centimetre. GazeParser reported a spatial error between 0.7° and 1.2°, this is quite similar to the performance of the ITU Gaze Tracker. TurkerGaze reported an error of 1.06°. These three eye trackers generally perform 25% worse in comparison to the high-end eye trackers. ITracker reported an error of 1.04 centimetre for mobile phones and 1.69 centimetres for tablets. 1.04 centimetre still is around 15% of the width of an iPhone, which begs the question do eye trackers provide useful data using mobile phones. 1.69 centimetre on a tablet does seem more reasonable.

5. Discussion

In this paper a list consisting of high-end eye trackers and webcam eye trackers was gathered. The eye trackers in this list were selected based on if they were still relevant. In the last decade many new webcam eye trackers have been created. An overview and comparison of these eye trackers does not exist yet, that is why creating this paper is relevant. Each of the eye trackers on the list were introduced and some general information about them was provided. From this information it became clear that a lot of the eye trackers were used for different purposes. This is why the eye trackers have been divided into groups to make the comparison between them more relevant. The comparison shows that while some webcam eye trackers have a lot of potential, others might need a little more improvement before providing useful data. High-end eye trackers still perform a significant margin better than webcam eye trackers when they are being used for specific research. On the other hand, webcam eye trackers have found a lot of effective uses in other areas such as webpage activity analyses and large-scale experiments. The way in which the high-end eye trackers can be compared to the webcam eye trackers is still quite restricted. The reported accuracy in the webcam eye tracker papers are not backed up by enough information to compare them to the high-end eye trackers. For instance the distance from the webcam to the screen and the size of the screen are rarely specified, which makes it very hard to calculate the accuracy in degrees of visual angle. The generalizability of the overview is limited based on the fact that none of the eye trackers have actually been tested, while writing this paper. The quality of the overview could be improved in the future if an evaluation of the usage of the eye trackers would be included as well.

6. Conclusion

In this paper we covered the process of gathering and analyzing 10 different eye trackers. 3 of these eye trackers were expensive high-end ones, while the other 7 were free options. Different approaches for eye tracking were discussed, different techniques were used to create eye tracking software. The different eye trackers were used for varying purposes, where some research teams aimed to reproduce some of the results of high-end eye trackers. Other ones used eye tracking with a more commercial thought. High-end eye tracking still provides the most accurate data, so for specific research of small eye movements using high-end eye trackers is still recommended. Webcam eye trackers can replace high-end eye trackers for some of the simpler eye movements without costing as much. New usages for eye tracking have opened up with the introduction of webcam eye trackers. If webcam eye trackers seem interesting definitely give them a try. Most of the webcam eye trackers are free anyway.

7. References

Carter, B. T., & Luke, S. G. (2020). Best practices in eye tracking research. *International Journal of Psychophysiology*, *155*, 49-62.

Ehinger, B. V., Groß, K., Ibs, I., & König, P. (2019). A new comprehensive eye-tracking test battery concurrently evaluating the Pupil Labs glasses and the EyeLink 1000. PeerJ, 7, e7086.

Eye tracker accuracy and precision. (2015). Tobii Pro. https://www.tobiipro.com/learn-and-support/learn/eye-tracking-essentials/what-affects-the-accuracy-and-precision-of-an-eye-tracker/

Eye tracker sampling frequency. (2016). Tobii Pro. https://www.tobiipro.com/learn-and-support/learn/eye-tracking-essentials/eye-tracker-sampling-frequency/

EyeLink 1000 Plus. SR Research. (2020, August 27). https://www.sr-research.com/eyelink-1000-plus/.

Farnsworth, B., PhD. (2019, April 2). What is Eye Tracking and How Does it Work? - iMotions. Imotions Publish. https://imotions.com/blog/eye-tracking-work/

Ghani, M. U., Chaudhry, S., Sohail, M., & Geelani, M. N. (2013, December). GazePointer: A real time mouse pointer control implementation based on eye gaze tracking. In INMIC (pp. 154-159). IEEE.

Hutton, S., Huang, Sui, Becker, Blair, Raffi, Khan, Metzner, Dillon, Valle, Gagl, Filik, Jacob, Nuthmann, Saint-Aubin, & Tseng. (2020, June 24). Highly Cited EyeLink Articles. SR Research. https://www.sr-research.com/eye-tracking-blog/eyelink-research-articles/highly-cited-eyelink-articles/.

Hutton, S. (2021, May 10). Visual Angle. Fast, Accurate, Reliable Eye Tracking. https://www.sr-research.com/eye-tracking-blog/background/visual-angle/

Johansen, S. A., San Agustin, J., Skovsgaard, H., Hansen, J. P., & Tall, M. (2011). Low cost vs. high-end eye tracking for usability testing. In CHI'11 Extended Abstracts on Human Factors in Computing Systems (pp. 1177-1182).

Kim, E. (2018). Potential of eye tracking technology for assessment of performance and medical education in the field of anesthesia. Korean journal of anesthesiology, 71(4), 253.

Krafka, K., Khosla, A., Kellnhofer, P., Kannan, H., Bhandarkar, S., Matusik, W., & Torralba, A. (2016). Eye tracking for everyone. In *Proceedings of the IEEE conference on computer vision and pattern recognition* (pp. 2176-2184).

Majaranta, P., & Bulling, A. (2014). Eye tracking and eye-based human–computer interaction. In *Advances in physiological computing* (pp. 39-65). Springer, London.

Nel, E. M., MacKay, D. J. C., Zieliński, P., Williams, O., & Cipolla, R. (2012). Opengazer: open-source gaze tracker for ordinary webcams.

Nyström, M., Niehorster, D. C., Andersson, R., & Hooge, I. (2021). The Tobii Pro Spectrum: A useful tool for studying microsaccades?. Behavior Research Methods, 53(1), 335-353.

Papoutsaki, A., Laskey, J., & Huang, J. (2017, March). Searchgazer: Webcam eye tracking for remote studies of web search. In Proceedings of the 2017 Conference on Conference Human Information Interaction and Retrieval (pp. 17-26).

Papoutsaki, A., Sangkloy, P., Laskey, J., Daskalova, N., Huang, J., & Hays, J. (2016). WebGazer: Scalable Webcam Eye Tracking Using User Interactions. Proceedings of the 25th International Joint Conference on Artificial Intelligence (IJCAI), 3839–3845.

Pupil Core - Eye tracking platform technical specifications - Pupil Labs. (2020). Pupil-labs. https://pupil-labs.com/products/core/tech-specs/

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. Psychological bulletin, 124(3), 372.

Rayner, K. (2009). The 35th Sir Frederick Bartlett Lecture: Eye movements and attention in reading, scene perception, and visual search. *Quarterly journal of experimental psychology*, *62*(8), 1457-1506.

San Agustin, J., Skovsgaard, H., Mollenbach, E., Barret, M., Tall, M., Hansen, D. W., & Hansen, J. P. (2010, March). Evaluation of a low-cost open-source gaze tracker. In Proceedings of the 2010 Symposium on Eye-Tracking Research & Applications (pp. 77-80).

Semmelmann, K., & Weigelt, S. (2018). Online webcam-based eye tracking in cognitive science: A first look. *Behavior Research Methods*, *50*(2), 451-465.

Sogo, H. (2013). GazeParser: an open-source and multiplatform library for low-cost eye tracking and analysis. Behavior research methods, 45(3), 684-695.

Spectrum: Most advanced eye tracking platform | Find out more. (2016). Tobii Pro. https://www.tobiipro.com/product-listing/tobii-pro-spectrum/

Voßkühler, A., Nordmeier, V., Kuchinke, L., & Jacobs, A. M. (2008). OGAMA (Open Gaze and Mouse Analyzer): open-source software designed to analyze eye and mouse movements in slideshow study designs. *Behavior research methods*, *40*(4), 1150-1162.

Wang, Q., Yang, S., Liu, M., Cao, Z., & Ma, Q. (2014). An eye-tracking study of website complexity from cognitive load perspective. *Decision support systems*, *62*, 1-10.

XLabs Pty Ltd, (2014) Eye / Gaze tracking system Technology Whitepaper, Australia. https://261f2cc8-8def-45d6-bf9a-00b0755e3fa3.filesusr.com/ugd/378c8a_76e0f65bddfc49d39f270fe687aaf155.pdf

Xu, P., Ehinger, K. A., Zhang, Y., Finkelstein, A., Kulkarni, S. R., & Xiao, J. (2015). Turkergaze: Crowdsourcing saliency with webcam based eye tracking. arXiv preprint arXiv:1504.06755.