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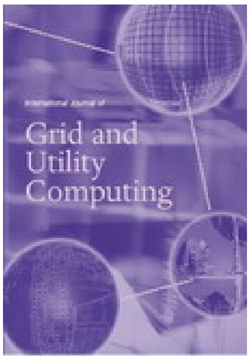

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A systematic review of eye-tracking data in NLP: exploring low-cost and cross-lingual possibilities

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Abstract: Integrating eye-tracking data into text processing models is consistently demonstrating improvements in their outcomes. Numerous studies have been undertaken to explore low-cost alternatives and investigate cross-lingual possibilities. In our systematic literature review, we provide an overview of the related studies, based on four main dimensions: eye-tracking in Natural Language Processing (NLP) subfields, cross-lingual eye-tracking, most relevant eye-tracking devices and low-cost eye-tracking opportunities. We highlight key studies showcasing that integrating eye-tracking data during training or testing improves the accuracy of NLP models in diverse subfields. There is a necessity to analyse eye-tracking data across different languages to explore cross-lingual patterns and variations. Furthermore, eye-tracking devices vary in form, sampling rate, accuracy and costs. Notably, low-cost devices are demonstrating acceptable accuracy rates, paving the way for a potentially cost-effective future in conducting eye-tracking experiments.

Keywords: eye-tracking; natural language processing; low-cost devices; cross-lingual eye-tracking.

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1 Introduction

The concept of eye-tracking involves capturing eye movements and offering valuable insights into human visual attention. Numerous studies illustrate how eye movements during reading indicate cognitive processes and comprehension of text.

Eye-tracking and text processing are intricately connected to each other, and combining these domains can enhance the performance of automated text processing models. Employing eye-tracking devices facilitates the evaluation of two reading dimensions: temporal and spatial. The temporal dimension pertains to the duration an individual concentrates on a particular word while reading. In contrast, the spatial dimension relates to the specific screen locations where readers direct their focus versus areas they overlook.

A proficient reader guides their eyes from one word to the next, prioritising key words that convey the text's essence. Key metrics gathered from eye-tracking experiments include fixation duration, focal points, saccades, scanning trajectory, gaze duration and overall viewing time.

Eye-tracking data has demonstrated its utility across diverse fields, such as psychology, linguistics, marketing, healthcare and human computer interaction.

In the context of this review, we are going to focus on the application of eye-tracking data to linguistic purposes and Natural Language Processing (NLP) subfields. Eye-tracking data can enhance various subfields of NLP such as evaluating machine learning model outcomes, refining parameters and attention mechanisms in neural networks, optimising automatic part-of-speech (PoS) tagging, Named Entity Recognition (NER) and sentiment analysis.

Currently, high-cost eye-tracking devices predominantly utilised in laboratory settings ensure precise and reliable studies. The aim is to enhance accessibility to track eye movements and related cognitive data.

The primary objective of this systematic review is to offer a comprehensive overview of key research endeavours undertaken in recent years at the intersection of eye-tracking and natural language processing, anchored by the four main research questions outlined in Sub-section 2.1.

While other review articles may focus on specific tasks within these domains, to the best of our knowledge they tend to provide an overview of specific tasks. In contrast, our aim is to present a broader perspective which encompasses some of the main relevant studies that emerging researchers in the intersection of these fields need to be familiarised with.

This review may serve as a valuable resource for these emerging researchers, aiming to familiarise them with pivotal studies in the domain, explore low-cost solutions, delve into cross-lingual opportunities and identify key data sets available for research.

The organisation of this review paper is divided into four main sections. Section 2 outlines the research methodology, focusing on four primary questions and primary criteria for collecting and selecting papers. Section 3 delves into the findings derived from addressing each research questions. Finally, Section 4 offers conclusions drawn from the outline and potential future work.

2 Research methodology

This systematic review follows the guidelines specified by Kitchenham and Charters (2007) to select the most relevant papers related to our research questions.

2.1 Research questions

The research questions addressed in our study are:

- *Research Question 1 (RQ1)*: Does the usage of eye-tracking data improve Natural Language Processing (NLP) models?
- *Research Question 2 (RQ2)*: Is there a need to create multilingual corpora for eye-tracking purposes?
- *Research Question 3 (RQ3)*: Which are the most relevant devices used to conduct eye-tracking experiments?
- *Research Question 4 (RQ4)*: Does the usage of low-cost eye-tracking devices provide a sufficient accuracy?

Several papers mention and discuss the benefits of gaze behaviour in various NLP tasks. Studying the relevant papers and answering the first research question will present the main benefits of using eye-tracking data in different fields of NLP. On the other hand, the contribution achieved by studying the second research question would be the listing of the advantages and disadvantages of multilingual corpora.

The answers to the third and fourth research questions are going to provide a list of the main eye-tracking devices, specifically low-cost equipment to emphasise the possibility of conducting accurate experiments even in low-cost scenarios. The main corpora and libraries created for eye-tracking purposes will be listed, so that to have a general overview of the existing eye-tracking data for research purposes.

2.2 Paper identification and selection

The relevant papers included in this systematic literature review have been selected from online databases such as ScienceDirect, IEEE Xplore, ACM Digital Library, Springer, ACL Anthology, arXiv and Google Scholar.

Considering the new advancements in this field, and previously published review articles related to the field of eye-tracking, we decided to consider papers from 2015 to 2023 in our review. Previous articles, particularly listed in the work of Carter and Luke (2020), present the best practices related to eye-tracking research up to 2019. This review offers a general overview of the practices involved in eye-tracking research. Consequently, we opted to limit our paper selection to the period spanning 2015 to 2023, adding specific papers related to our research questions, not previously listed in the work of Carter and Luke (2020) for the period 2015 to 2019 and extending our review with the latest advancement after 2019. Based on our opinion, the choice of the period 2015 to 2023 encompasses both emerging studies and refinement of earlier research efforts, reflecting the improvements done in the field of eye-tracking over the last years.

The main research terms we used are: 'eye-tracking', 'low-cost eye-tracking', 'gaze estimation' and 'natural language processing'.

Table 1 provides a summary of the inclusive and exclusive criteria, while Table 2 illustrates the papers selected from each of the mentioned databases.

Table 1 Inclusive and exclusive criteria

Digital Databases	ScienceDirect, ACM Digital Library, IEEE Xplore, ACL Anthology, Springer, Google Scholar
Search Terms	Eye-tracking, low-cost eye-tracking, natural language processing
Information saved	List of authors, title of papers, year of publication, digital object identifier (DOI), abstract
Inclusive criteria	• The study describes the usage of eye-tracking techniques in natural language processing tasks. • It is published in journals or conference proceedings. • It is part of the primary research group. • The study has been published in English.
Exclusive criteria	• The study is not related to computer science. • The study does not describe methods related to NLP or eye-tracking. • The study has not been published between 2015 years and 2023 years.

Initially collected papers in this systematic review was 260, of which, after following the inclusive and exclusive criteria, 56 papers were selected to be included in the final work.

In the total number of references, we have 56 references of the selected papers and one reference of the research methodology used. This paper represents a refined and expanded version of our prior study Haveriku et al. (2024) which originally focused on the analysis of only 23 papers.

Meanwhile, from the 56 selected papers, we ought to mention that the work of Kennedy et al. (2003) and Lecun et al. (1998) have been included in this review even though they fulfilled the exclusive criteria of being published before 2015. We deliberately included these two papers, since the first one presents a commonly used eye-tracking corpus, while the second one provides a Convolutional Neural Network (CNN) architecture for eye detection.

Table 2 Summary of the selected research works

Digital database	*Initially collected papers*	*Papers selected after checking the title and abstract*
Science Direct	150	25
ACM Digital Library	50	10
IEEE Xplore	35	7
Other (ACL Anthology, Google Scholar, Springer)	25	14
Total	260	56

3 Research analysis and findings

3.1 RQ1: Does the usage of eye-tracking data improve natural language processing (NLP) models?

The usage of eye-tracking techniques in natural language processing tasks, has been highlighted in various research works, such as Part of Speech (PoS) tagging, text summarisation, sentiment analysis, entity recognition and so on. In this section, we are going to provide a summarisation of the most relevant works, based on the NLP subfield, the corpus used, the type of model and the improvement in accuracy which has been achieved when eye-tracking data is included in the model.

Table 3 presents a summarisation of the reviewed papers, providing a good source of information for anyone interested to dwell further in the field.

Table 3 Eye-tracking in NLP subfields

Authors and publication year	*The NLP subfield*	*Corpora*	*Type of model*	*Accuracy achieved*
(Barrett and Søgaard, 2015)	- Syntactic categories	250 sentences from: Wall Street Journal articles, Wall Street Journal headlines, emails, weblogs and Twitter.	Supervised Logistic Regression	80.7–83.7%
(Barret et al., 2016)	- PoS Tagging	Dundee Treebank Penn Treebank PoS annotation	Unsupervised model Data used during training and testing time	79.77–81.00%
(Mishra et al., 2017)	- Sentiment Analysis - Sarcasm Detection	Dataset 1: 994 texts: 383 positive, 611 negative, 350 sarcastic. Dataset 2: 1059 texts: positive, negative and objective.	Support Vector Machine Naïve Bayes Multi-layers Neural Network	Improvement of 3.7% in the first data set and – 9.3% in F-score in the second data set

Table 3 Eye-tracking in NLP subfields (continued)

Authors and publication year	*The NLP subfield*	*Corpora*	*Type of model*	*Accuracy achieved*
(Rohanian et al., 2017)	- Predicting multiword expressions	GECO corpus	- Conditional Random Fields (CRF) - Data used during training and testing time.	F1 score 70.05 for the first word and 54.0 for the last word in the expression
(Barret et al., 2018)	- Sentiment analysis - Grammatical error detection - Detection of abusive language	Dundee corpus ZuCo corpus	- Bidirectional LSTM	Reduction of mean error from baseline models of 4.5%
(Strzyz et al., 2019)	- Dependency parser	Parallel data Dundee corpus, Dundee treebank. Disjoint data Penn treebank (*parsing*) and Dundee Treebank (*eye-movement*).	- BiLSTM model - Data used during training time	Parallel setup: 85.36–85.61 Disjoint data: 93.98–94.12
(Klerke and Plank, 2019)	- Syntactic Tagging	Dundee Corpus. Ghent Eye-Tracking Corpus (GECO)	- BiLSTM model	Dundee: 95.25–95.48 GECO: 95.25–95.41
(Hollenstein and Zhang, 2019)	- NER	Dundee Corpus. GECO corpus. ZuCo corpus.	- BiLSTM model - Gaze feature in an embedding layer	Precision: 86.92–89.04
(Chen et al., 2022)	- Sentiment Analysis	1224 microblogging Emotions: positive, neutral, negative (408 for each); Chinese language	- Hierarchical Attention Networks - Reinforcement learning	2.13% improvement in F1-sore
(Bautista and Naval, 2020)	- Predicting gaze features for each word	ZuCo, Provo Corpus UCL Corpus, GECO	- Bi-LSTM model	Improvement of 2.67%.

The data presented in Table 3 demonstrate the increased number of research papers which leverage the usage of gaze data in estimating and optimising reading behaviour. The results achieved by Barrett and Søgaard (2015); Barret et al. (2016); Strzyz et al. (2019) and Klerke and Plank (2019) proved that the usage of gaze features can improve the performance of PoS taggers and dependency parsers, even when there is a small amount of data available. Strzyz et al. (2019) proposed a new approach, that uses gaze features to improve previously annotated treebanks without annotated gaze.

Mishra et al. (2017); Barret et al. (2018) and Chen et al. (2022) presented relevant works that show the advantages of using eye-tracking data in sentiment analysis tasks. Mishra et al. (2017) used two publicly available data sets to detect sarcasm and annotate sentiments. The two data sets are enhanced by adding gaze features and fed into three different classifiers: Naïve Bayes, Support Vector Machine (SVM) and a multi layered neural network. The best results were achieved by the SVM classifier which achieved a relevant improvement of 6.1% in the F1-Score, when the gaze features were added. Furthermore, the authors focus on the necessity to use inexpensive mobile devices so that to make the process of collecting eye-tracking data more practical and extensive.

Barret et al. (2018) conducted experiments in three NLP subfields: grammatical errors, abusive language detection and sentiment analysis. The main achievement of the authors was proving that the information from human attention can provide an inductive bias which is useful in the improvement of recurrent network architectures. Chen et al. (2022) built a model by adding human behaviour. This model achieved an improvement of 2.13% in F1-Score (Haveriku et al., 2024).

Other relevant achievements are presented in Rohanian et al. (2017) where the authors focus in the automatic identification of multi-word expressions, and the impact of gaze features in the existing models. On the other side, Hollenstein and Zhang (2019) focused on improving Named Entity Recognition by adding eye-tracking data. The most meaningful results achieved from the authors were: (1) Adding gaze features on word level eliminates the necessity to include gaze data at testing time; (2) Classical NER models are outperformed by NER models augments with gaze information (Haveriku et al., 2024).

3.2 RQ2: Is there a need to create multilingual corpora for eye-tracking purposes?

Most studies in the field of eye-tracking have been done for languages with a high usage such as English and German. Therefore, there is an increase demand to broaden research efforts for low-resource languages. In studies related to reading, it is crucial to study the variations across different written languages. Understanding the impact of eye movements in reading processes becomes essential.

In this section, we focus on key existing data sets and primary studies that highlight the importance of multilingual data sets and research. In Table 4, we present some of the most important one and multilingual data sets.

Table 4 One and multilingual eye-tracking data sets

Corpus	*Number of participants*	*Languages included*
(Raymond et al., 2023)	40 participants 97 trials	English, Spanish, Chinese, Hindi, Russian, Arabic, Japanese, Kazakh, Urdu, Vietnamese
Dundee Corpus (Kennedy et al., 2003)	10 participants	English, French
GECO (Cop et al., 2017)	33 participants	English, Dutch
ZuCo Corpus (Hollenstein et al., 2018)	12 participants	English
MECO (Slegelman et al., 2022)	580 participants	Dutch, English, Estonian, Finnish, German, Greek, Hebrew, Italian, Korean, Norwegian, Russian, Spanish and Turkish
Russian Sentence Corpus (Laurinavichyute et al., 2018)	96 participants	Russian
RatrOS Corpus (Leal et al., 2022)	393 participants	Brazilian Portuguese
The Provo Corpus (Luke and Christianson, 2017)	84 participants	English
WebQAmGaze (Ribeiro et al., 2023)	332 participants	English, Spanish and German
CopCo (Hollenstein et al., 2022)	22 participants	Danish
RaCCooNS (Frank and Aumeistere, 2023)	37 participants	Dutch

Raymond et al. (2023) presented an open access reading data set, where they include several languages which are underrepresented in eye-tracking research. The authors identify two main reasons for the limited linguistic diversity in eye-tracking data sets: economic constraints due to high expenses of devices and software, and a predominant focus on eye trackers designed for Latin languages. Future efforts will involve gathering data for not previously represented languages such as Ukrainian, Telugu and indigenous African languages.

Hollenstein et al. (2018) created Zurich Cognitive Language Processing Corpus (ZuCo), where they Combined Electroencephalography (EEG) with eye-tracking information. The whole data set is composed of EEG and eye tracking data of 21.629 words, in total 154.173 fixations. Their work, by integrating EEG and eye tracking data, offer an asset for upcoming research and for refining machine learning models for tasks such as relation extraction, sentiment analysis and entity recognition.

Additionally, there's the RatrOS corpus, developed by Leal et al. (2022), which consists of eye tracking data gathered from university students in Brazilian Portuguese (Haveriku et al., 2024).

Slegelman et al. (2022) examined 13 different languages to explore variations in reading behaviour across different languages. They developed MECO, a multilingual corpus of eye movement to differentiate eye-tracking patterns across languages. A key insight from their research indicates that the skipping rate among languages has a considerate difference, a finding attributed by the authors to varying word length distribution across languages. The authors suggest as possible future research directions, the study of the impact of word frequency and length, emphasising that the skipping and fixation probabilities are the two main features that vary across linguistic contexts.

Other research works present results of the comparison between different languages. Barret et al. (2016) studied the correlation between PoS and gaze in two languages: French and English. The authors show that English gaze data can assist NLP models designed for the French language, indicating that gaze based PoS tagging models can be applied across different languages. The experiments utilised segments of data from the Dundee eye-tracking corpus.

Hollestein et al. (2021) analysed the performance of multilingual models to predict reading behaviour.

The languages included in their research are Dutch, German, English and Russian. The authors use the BERT and XLM models to predict eye tracking features, demonstrating that the BERT model gives a better generalisation across different languages. The XLM model achieves a better level of performance on smaller amounts of data. The results achieved from the authors of this paper demonstrate that multilingual models can predict gaze pattern during reading, even in the case when the language used is not included in the fine-tuning process. Even though the study is limited to four languages, it demonstrates the generalisation of insights gained from one language to another.

The results achieved from analysing the papers in this research question suggest the universality of cognitive processes on reading time, regardless of linguistic diversity. Future work, include the exploration of a broader range of languages, and characteristics of linguistic structures that influence the reading behaviour.

The main benefit of multilingual corpora is to enable researchers to compare gaze patterns across various languages, leading to insights for universal reading processes and language specific factors. Previous research has shown that aspects of reading behaviour such as fixation durations and saccade length are consistent across languages (Slegelman et al., 2022). However, other reading aspects which can be leveraged in the future are orthographic, phonological and syntactic properties.

Furthermore, studies such as Barret et al. (2016) and Hollestein et al. (2021), demonstrate that features extracted from eye-tracking data can be generalised across languages, facilitating cross-lingual predictions of reading behaviours.

The cross-lingual study of eye-tracking data is an emerging field, leading to the necessity of multi lingual corpora so that to better understand how cross-lingual variations in eye-movements can improve computational models, such as machine translation systems, the potential application in computational linguistic and language learning strategies.

3.3 RQ3: Which are the most relevant devices used to conduct eye-tracking experiments?

After highlighting key papers on eye-tracking research within NLP, it's crucial to outline the primary devices employed in these experiments. Table 5 will enumerate the principal devices, specifying which ones were utilised to create the data sets referenced in Table 4 and execute the experiments detailed in Table 3.

Table 5 Eye-tracking devices

Device Name	*Producer*	*Sampling rate (Hz)*	*Accuracy*	*Related papers*
Tobii X120	Tobii	60/120	0.5 degree	(Barret et al., 2016; Cop et al., 2017)
Tobii T120	Tobii	120	0.5 degree	(Barrett et al., 2016)
Tobii X2-30 (*Discontinued;Replaced by Tobii Pro Nano*)	Tobii	30	0.5 degree	(Cheng et al., 2022)
Tobii Pro Nano	Tobii	60	0.3 degree in optimal conditions	–
Tobii Pro Spark	Tobii	60	0.4 degrees in optimal conditions	–
Tobii Pro Fusion	Tobii	30/60/120/250	0.3 degrees in optimal conditions	–
Tobii Pro Spectrum	Tobii	1200	0.3 degree in optimal conditions	–
EyeLink II	SR Research	500	0.50 degree	–
EyeLink Portable Duo	SR Research	2000	0.25–0.50 degree	(Gunawardena et al., 2022)
EyeLink 1000	SR Research	250/500/1000/2000	0.25 to 0.5 degree	(Barrett et al., 2016; Frank and Aumeistere, 2023; Gunawardena et al., 2022; Hollenstein and Zhang, 2019)
EyeLink 1000+	SR Research	2000	0.25 to 0.50 degree	(Eide et al., 2019; Gomez-Poveda and Gaudioso, 2016; Gunawardena et al., 2022; Haveriku et al., 2024; Hollenstein et al., 2022; Hollestein et al., 2021; Hosp et al., 2020)
Pupil Neon	Pupil Labs	220	2.4 degree uncalibrated 1.6 degree with offset correction	–
Pupil Core	Pupil Labs	200	0.6 degree	–
Logic One	EyeLogic	60/120/250	<0.5 degrees	–
Lite	EyeLogic	60/120	<0.5 degrees	–
GazePoint GP3 (Ivanchenko et al., 202020)	GazePoint	60	92.5% sensitivity 76.8% specificity	(Brand et al., 2021)

As indicated in the last column of Table 5 the main eye-tracking devices, used in eye-tracking studies during reading consist of Tobii and EyeLink. Notably, EyeLink 1000+ is recognised for its accuracy in eye-tracking. This distinction is shown by its widespread utilisation in eye-tracking while reading corpuses and usage in experimental configurations.

3.4 RQ4: Does the usage of low-cost eye-tracking devices provide a sufficient accuracy?

The usage of the data collected from eye-tracking experiments provides a series of benefits and improvements in the automatic text processing algorithms. The devices presented in Table 5 compose the traditional requirements in eye-tracking research. Even though, the best way to collect highly accurate data until now is by using high quality equipment, such as the ones presented above, several research works are evaluating the possibilities to use simple and mobile cameras incorporated in mobile devices, to conduct eye-tracking experiments.

The difficulties and high costs related to eye-tracking experiments are making it more important to deepen the research in low-cost eye-tracking experimental setup. Table 6 lists the main existing data sets captured from normal web or mobile cameras.

In the research of Krafka et al. (2016) was created the first data set of large scale for eye-tracking in mobile devices. GazeCapture contains data from 1450 people with a total of 2.5 million frames captured. Their CNN model iTracker has achieved a prediction error of 1.71 cm in mobile phones and 1.34 cm with calibration. By applying the features learned from their model in other data sets the authors evaluated the generalisation of these features. Gunawardena et al. (2022) proposed a mobile edge architecture which estimates gazes on mobile devices.

The authors have used 1.4 million frames for face and eye detection from the GazeCapture (Krafka et al. 2016) data set and compares the results achieved from using four CNN architectures: AlexNet (Krizhevsky et al., 2017), LeNet-5 (Lecun et al., 1998), MobileNet (Howard et al., 2017) and ShuffleNet (Zhang et al., 2018). Despite comparing several algorithms, the authors have tested the performance of their model in different modes: on device, using the cloud and edge computing. The main findings of their work are a) the MobileNet-V3 and ShuffleNet-V2 models provide the smallest prediction error's value, and b) edge computing provides the best user experience in eye-tracking applications in mobile devices.

Ribeiro et al. (2023) created WebQAmGaze as a multilingual data set which comes with low cost, since it is composed of data collected from normal web cameras. The data set contains data from natural reading in English, Spanish and German texts. The researchers compared the results from the data collected from web cameras and the data collected from commercial eye tracking devices so that to evaluate the accuracy of their method.

Different from the works listed above, WebQAmGaze is the first work which provides gaze features in word levels while using a webcam. The previously mentioned work was based on analysing data from participants viewing images or videos. Even though the experiments result in good accuracy, future work which can be conducted to improve and enlarge the usage of low-cost devices for eye tracking experiments is the inclusion of better algorithms to estimate fixation and to use language models such as BERT.

In Table 7, we have listed some of the main libraries and algorithms which has been developed to leverage the accuracy of low-cost eye-tracking setups.

Table 6 Web camera and mobile data sets

Name	*No. participants / Dimensions*	*Error*	*Characteristics*
GazePoint (Krafka et al., 2016)	1.450 participants 2.5 million frames	Prediction error: 1.71 in mobile phones (without calibration) 1.34 in mobile phones (with calibration)	Mobile device camera (images)
TabletGaze (Huang et al., 2015)	51 subjects 4 postures 35 gaze locations	Mean error: 3.17 cm	Tablet front-facing camera (images)
TurkerGaze (Xu et al., 2015)	3 participants 20.608 images	Median error: 1.06 degree	Webcam-based (images)
MPIIGaze (Zhang et al., 2015)	15 participants 213.659 images	Mean prediction error: 13.9 degrees	Webcam-based (images)
ETH-XGaze (Zhang et al., 2020)	110 participants 1 million samples	Gaze estimation errors in degrees: 4.2–5.4	18 digital SLR cameras
WebQAmGaze (Ribeiro et al., 2023)	332 participants	Accuracy: 70.3 to 73.4%	Webcam-based

Table 7 Eye-tracking libraries and system

Author & Year	*Name*	*Characteristics*
(Papoutsaki et al., 2016)	WebGazer	JavaScript library
(Cheng et al., 2022)	EasyGaze	Unity
(Muller and Mann, 2021)	GazeClassify	Python package
(Papoutsaki et al., 2017)	SearchGazer (WebGazer extension)	JavaScript library
(Augereau et al., 2018)	Vocabulometer	Web platform
(Park and Park, 2016)	Low-Cost Real-time Eye Gaze System	Hardware device; Driver; Software
(Hosp et al., 2020)	Tracking eye movements with high-speed	Hardware device C/C++, OpenCV
(Rakhmatulin and Duchowski, 2020)	Deep Neural Network for low-cost eye-tracking	Python, OpenCV
(Taban et al., 2018)	Eye-tracking mobile application	Android Studio, OpenCV

Papoutsaki et al. (2016) presented a JavaScript library, named WebGazer. This library provides the possibility to self-calibrate the model by observing the visitors of web pages through normal web cameras or the camera of mobile devices. This library can be easily integrated in websites with a few lines of code and provides the possibility to detect the pupil and estimate gaze using regression analysis. The authors evaluated the accuracy of the library by conducting an online study which proved the efficiency of WebGazer, its accuracy to detect the gaze of users and continuously learn from the interaction of the user.

Cheng et al. (2022) proposed a hybrid method for eye-tracking in mobile devices, where they compare different image resolutions and illuminations to achieve the best result possible. The present EasyGaze as an approach which uses images captured from a RGB camera and conducted a study with twelve participants on a smartphone with Android OS. The method provided by the authors provided advantages such as: good performance in various illumination conditions, good performance with low image resolution of 26 × 13 pixel and easily implementable on mobile devices.

Muller and Mann (2021) introduced GazeClassify as an open-source package written in Python to automatically annotate eye-tracking data collected from the camera of mobile devices. This algorithm showed good results compared to the manual identification of gaze from three chosen annotators. The Vocabulometer is a web platform presented by Augereau et al. (2018), compatible with Tobii 4C and Tobii Eye X, which records the reading habits of users and helps in analysing the words where the user is focused more and the users' reading habits.

Park and Park (2016) dedicated their work to the creation of an efficient algorithm to detect pupils in real time eye-tracking systems.

The proposed method, called 'Low-cost real-time eye gaze system' (Hosp et al. 2020) evaluated a low-cost system which tracks eye movements with high-speed. The authors evaluated methods to detect glints and pupils in high-speed movements. They used C/C++ to develop their software and libraries such as OpenCV and Qt, providing image capturing, glint and pupil detection. Their proposed system comes with a total cost of 600 euros and achieved an average precision of 0.38 degrees. The model was tested on 19 participants, estimating a best accuracy of 0.5 degrees and the worst accuracy of 1.4 degrees.

Rakhmatulin and Duchowski (2020) considered the usage of deep neural network to increase the accuracy of low-cost devices for eye-tracking. The authors present a method to track gaze, determining the necessity of creating low-cost devices for eye-tracking experiments and focus on the need of standardisation in the eye-tracking field so that to allow comparison between different research papers.

Taban et al. (2018) created a mobile application which provides the possibility to select buttons by moving eyes, using the built-in front camera. The application was built using the Android Studio environment and the OpenCV library. After testing the app on a Huawei tablet the accuracy achieved for the model is 66% indoors and 76% in outdoor spaces.

Extensive work has been done in improving the accuracy of low-cost systems. Despite the work done to create various low-cost systems, libraries and algorithms as previously mentioned in Table 7, other authors have focused in areas such as feature selection, pupil detection, calibration, error prediction and building devices with low costs listed in Table 8.

Table 8 Research areas in low-cost eye-tracking

Research area	*Papers*
Feature selection	(Aunsri and Rattarom, 2022)
Pupil detection	(Gomez-Poveda and Gaudioso, 2016)
Calibration	(Lei, 2021; Li et al., 2022; Khonglah and Khosla, 2015)
Error Predictions	(Wisiecka et al., 2022; Saxena et al., 2022)
Building low-cost devices	(Wang et al., 2016; Changwani and Sarode, 2019; Mounica et al., 2019; Luo et al., 2019; Eide et al., 2019; Ivanchenko et al., 2020)

In their research, Aunsri and Rattarom (2022) proposed the selection of new set of eye-based features which provide a better performance in real-time applications and fit systems with low-cost devices. The features they choose capture both head movements and positions of the eyes regarding the screen. The efficiency of the features they have chosen are tested using several machine-learning algorithms, achieving a recognition rate of 93.94%.

Meanwhile, Gomez-Poveda and Gaudioso (2016) proposed a metric to estimate the stability of pupil detection. They presented a measure for pupil detection which can be implemented in existing algorithms to increase the detection accuracy. This metric can be used to make comparison for the temporal stability of different eye-tracking algorithms.

Several works are related to the calibration process in terms of low-cost eye-tracking since calibration is one of the most important parts to preserve the accuracy of the collected data. Lei (2021) has focused their work on the calibration of front cameras in mobile devices so that to properly track eye movements. The author describes the instability of distance between the user and the phone, relevant noises in the environment such as lack of lightning, camera resolution, etc.

Li et al. (2022) in their research work studied an estimator of the possible calibration errors during gaze estimation. The authors studied calibration errors considering facial features and the Monte Carlo perspective. Khonglah and Khosla (2015) presented an infrared based technique, to demonstrate the usage of a low-cost webcam-based setup that does not require any calibration at all. The results achieved from their work aims to assist young children with autism.

Wisiecka et al. (2022) conducted a study to compare the prediction errors of webcam eye-tracking to remote eye-tracking. They compared web camera conditions using an online software RealEye with remote condition prepared by using PsychoPy and GP3 eye tracker. The total number of participants in this study was 83 students and the final conclusions demonstrated that eye-tracking conducted by using webcam is a good low-cost alternative to eye-tracking devices with higher costs.

Saxena et al. (2022) proposed the application of deep learning methods for eye-tracking in online experiments. They resulted in the conclusion that the combination of device calibration, gaze calibration and the performance of the deep learning model offer an improved accuracy of 2.58 degrees, in regard with previous eye-tracking experiments.

Other works present several low-cost forms of eye-tracking. An example is the work of Wang et al. (2016) where the authors present a low-cost system, with an estimated cost of 38 USD, which comes in the form of eye-tracking head-mounted glasses. The mean error of gaze estimation produced by their system is 0.5748 degrees. Changwani and Sarode (2019) proposed a 50 USD setup, composed of two cameras which track iris and head movements. With the combination of computer vision and neural networks the authors aim to predict where a user is looking based on the data collected from the two cameras.

Mounica et al. (2019) proposed a system using the web camera and computer vision libraries. Luo et al. (2019) conducted an experiment with 15 participants, using Tobii Eye Tracker 4C, with an estimated cost of 169 USD, achieving an accuracy of 97.85% (SVM classifier). Eide et al. (2019) compared a low-cost eye-tracker EyeX with a higher costing one TX300 to detect oculomotor problems in 39 children, resulting in similar results between the two devices. Ivanchenko et al. (2020) built a low-cost eye tracker, the characteristics of which include automated calibration, measurement of noises, the detection of blinks and analysis of pupil centration. They evaluated their model making measurements with 10 participants, reaching the result that their device is a good resource for binocular eye tracking.

4 Conclusions and future work

The integration of eye-tracking data to leverage NLP models reveals promising outcomes. Numerous studies have underscored that the incorporation of gaze information during training or testing phases significantly improves the accuracy of machine learning and neural network models, in fields such as sentiment analysis and PoS tagging.

A challenge in this domain is the expansion of eye-tracking data across different languages, particularly low-resource languages. Future work in this domain can identify similarities and divergences in human reading behaviour across different languages. Furthermore, emerging research are showing the feasibility of utilising low-cost possibilities, including web cameras, or integrated mobile device cameras.

This review article demonstrates the potential of eye-tracking data in NLP subfields, highlighting the significance of cross-lingual research and challenges related to cost considerations. Future research in the field is necessary to underscore the importance of accessibility, cross-lingual data sets and device availability.

From the results achieved in this systematic review, we aim to enhance research in the area of eye-tracking in our current laboratory settings. The main advancements that we aim include:

- Leveraging the results achieved from RQ1, which demonstrate that eye-tracking data can leverage models in various subfields of NLP. We plan to integrate eye-tracking data into our existing NLP research efforts for Albanian language, improving the current model performance. These results can be beneficial and impactful for other NLP researchers interested in the field of eye-tracking.
- Building on findings from RQ2, which indicate the transferability of gaze data between languages, we intend to explore in the future the applicability of English gaze data to enhance NLP models for Albanian. This kind of investigation can be extended to other languages.
- Exploiting low-cost eye-tracking opportunities, highlighted in RQ4, such as utilising web or mobile cameras, using libraries such as WebGazer (Papoutsaki et al., 2016), SearchGazer (Papoutsaki et al., 2017) and GazeClassify (Muller and Mann, 2021) to develop an eye-tracking corpora for Albanian language.
- Establishing a platform for collecting eye-tracking data with low-cost devices will underscore the benefits of integrating eye-tracking data in NLP problems, potentially motivating further investiment in advanced equipment for improved research outcomes. RQ3 emphasised that one of the main devices used for

eye-tracking purposes is the EyeLink 1000+. Successful outcomes with low-cost devices may lead to future investments in a more advanced device such as EyeLink 1000+.

Finally, we aim to extend this systematic literature review after 5 years, hoping to incorporate our own research work and contribute to the advancement of eye-tracking research, particularly in the context of NLP and low-resource languages.

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