Performing Audiometry using Pupillometry: State-of-the-Market and Sensor Selection

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Abstract. Hearing impairment poses a significant global health challenge, impacting millions of individuals across all age groups. Early detection and intervention are paramount, especially in infants and young children, to mitigate the adverse effects on speech, language, and cognitive development. Traditional audiometry methods, however, rely on subjective patient responses, rendering them unsuitable for non-collaborative individuals such as infants, newborns, and those with cognitive impairments. To address this limitation, the APURE (Audiometry with PUpil REsponse) project seeks to develop an objective audiometer leveraging pupillometry, the measurement of pupil size and reactivity. This paper presents a comprehensive state-of-the-market survey of eye-tracking systems, a crucial step in identifying the most suitable sensors for the APURE project.

Keywords: Pupillometry · Objective Audiometry · Eye-Tracking · Sensor Selection · Hearing Impairment

1 Introduction

Hearing impairment is a prevalent condition affecting millions of people worldwide [16]. Early detection and intervention are crucial for mitigating its impact on speech, language, and cognitive development, particularly in infants and young children. Traditional audiometry relies on subjective responses from patients, making it unsuitable for those unable to provide reliable feedback, such as infants, newborns, and individuals with cognitive impairments. This limitation necessitates the development of objective audiometry methods that can accurately assess hearing capabilities without requiring active participation from the patient.

Recent advancements in pupillometry, the measurement of pupil size and reactivity, have shown promise in the field of objective audiometry. Studies have demonstrated a correlation between Pupil Dilation Response (PDR) and auditory stimuli, suggesting that PDR could serve as a physiological indicator of sound detection and perception [1]. This non-invasive technique offers a potential solution for evaluating hearing thresholds in non-collaborative patients, as it does not rely on subjective reports or behavioral responses.

In this context, it is worth to remark the impact that the Internet of Things (IoT) has in eye tracking technology. As in many other applications of healthcare domain [11, 4, 5, 14], eye tracking technology analyzes ocular movements and is a beneficiary of IoT advancements both in terms of enhanced connectivity and data processing capabilities. Conventional eye tracking systems, often constrained by standalone devices with limited computational and storage capacities, generally deployed in clinical settings, are nowadays transformed by IoT integration. This process facilitates connection to cloud services, increasing computational resources for instantaneous data analysis and implementation of machine learning algorithms. Consequently, this enhanced connectivity enables more sophisticated interpretation of ocular movement patterns, pupil response, gaze analysis and, in general, insights on human vision.

An important impact of IoT on eye tracking is the facilitation of real-time data acquisition and remote monitoring. In the healthcare domain, for instance, eye tracking serves as a valuable tool for monitoring patients with neurological conditions [3]. IoT-enabled eye trackers can continuously gather and transmit data to healthcare providers without delay. This capability enables early detection of anomalies and allows for timely interventions, ultimately improving patient outcomes. Similarly, in the marketing sphere, real-time data from IoT-integrated eye trackers provides immediate feedback on consumer behavior, enabling dynamic adjustments to advertising strategies.

In this context, the APURE (Audiometry with PUpil REsponse) project aims to leverage pupillometry to develop an objective audiometer that can be used in clinical settings. The project's primary objectives are to:

1. Develop an effective audiometry test for non-collaborative patients and validate it against gold-standard audiometry tests.
2. Provide an open biomedical solution for investigating the correlation between pupil response and focus on demanding tasks or emotional states.

To achieve these objectives, the APURE project will integrate expertise from various disciplines, including audiology, engineering, and computer science. The project will focus on developing a pupillometry system that can accurately measure pupil size and reactivity in response to auditory stimuli. The system will incorporate advanced signal processing and machine learning algorithms to analyze the collected data and correlate it with hearing thresholds. Preliminary results of the project and data collected in this first stage are available in [10]. In particular, the data collected in this work can be further analyzed to explore the correlation between physiological pupil responses to auditory stimuli and the emotional state of the user. The results could determine whether PDRs are a viable alternative or complement to traditional audiometric hearing tests in patients with limited responsiveness. They may also help to clarify how the visual and auditory systems work together to detect and localize external sounds.

The successful development and validation of an objective audiometer based on pupillometry would have a significant impact on the field of audiology. It would enable early detection and intervention for hearing impairments in populations that were previously difficult to assess, leading to improved outcomes for these individuals. Additionally, the open biomedical solution resulting from the project could contribute to research in other areas, such as cognitive science and psychology, where pupil response is used as an indicator of cognitive load or emotional state [6].

In this paper, we present a comprehensive survey of the eye-tracking sensor market, examining the strengths and weaknesses of various commercially available and open-source solutions. The survey will consider the specific requirements of the APURE project, with a particular emphasis on balancing performance, cost, and accessibility. By identifying the optimal sensor technology, we aim to pave the way for the development of an affordable, accurate, and user-friendly objective audiometer that can be readily deployed in clinical settings, ultimately improving the diagnosis and treatment of hearing impairments in diverse populations.

1.1 Sensor Selection Requirements

A comprehensive state-of-the-market survey is essential for identifying the most suitable sensors for the APURE project. The survey will target eye-tracking systems due to their non-invasive and convenient approach to measuring pupil response in real-world settings. The key characteristics to be evaluated include:

1. **Accuracy:** The accuracy of pupil size and reactivity measurements are critical for reliable audiometry results. The survey will assess the performance of different eye-tracking systems in terms of their ability to accurately track pupil movements and measure changes in pupil size. The range of accuracy has been set to $\leq 0.8°$.
2. **Sampling Rate:** The sampling rate of the eye-tracking system determines the temporal resolution of the pupil response data. A higher sampling rate allows for more detailed analysis of the PDR, which is crucial for identifying subtle changes in pupil size that may be indicative of hearing thresholds. The survey will evaluate the sampling rates of various eye-tracking systems and their suitability for capturing the dynamic nature of the PDR. The range of sampling rate has been set to ≥ 50 Hz.
3. **Field of View:** The Field of View (FOV) of the eye-tracking system refers to the angular extent of the observable area. A wider FOV allows for greater flexibility in head movements and gaze direction, which is important for ensuring the comfort and natural behavior of the patient during audiometry testing. The survey will compare the FOVs of different eye-tracking systems and their impact on user experience.

4. **Illumination:** The illumination conditions under which the eye-tracking system operates can significantly affect the quality of pupil measurements. Some systems may require controlled lighting environments, while others may be more robust to variations in ambient light. The survey will assess the performance of different eye-tracking systems under various illumination conditions to determine their suitability for clinical use.
5. **Data Processing and Analysis:** The ability to process and analyze the collected pupil response data is crucial for extracting meaningful information about hearing thresholds. The survey will evaluate the data processing capabilities of different eye-tracking systems, including their ability to filter noise, detect artifacts, and extract relevant features from the pupil response data.
6. **Cost and Accessibility:** The cost and accessibility of eye-tracking systems are important considerations for their widespread adoption in clinical settings. The survey will compare the prices of different systems and assess their availability to healthcare providers and researchers. The range of cost has been set to $\leq$15k€.

By conducting a thorough state-of-the-market survey, the APURE project can identify the most appropriate eye-tracking sensors that meet the project's requirements in terms of accuracy, sampling rate, field of view, illumination, data processing, and cost. This will ensure that the developed audiometer is equipped with the best possible sensors for measuring pupil response and providing accurate and reliable audiometry results.

Due to space limitations, we present the most representative candidates from the available devices on the market, selected for their strong potential. Our selection is based on how well these devices meet the requirements outlined above and their key peculiarities, particularly those most useful for achieving the objectives of the APURE project.

2 State of the Market Survey

The state-of-the-art in eye-tracking technology is constantly evolving, with new systems and features emerging regularly. The following presents a comparative analysis of several prominent eye-tracking systems, considering the key characteristics relevant to the APURE project:

- **Pupil Labs Pupil Core[3]:** This open-source platform offers high accuracy (0.6 degrees) and a sampling rate of up to 200 Hz. Its 120-degree field of view allows for flexibility in head movements, and it is robust to varying light conditions. The open-source software provides extensive analysis tools, making it accessible and customizable for researchers and developers. Pupil Core has been used in various research studies, including investigations of cognitive processes and attentional mechanisms [12].

[3] https://pupil-labs.com/products/core

- **Tobii Pro Glasses 3[4]:** This system offers high accuracy (0.6 degrees) and a sampling rate of up to 100 Hz. Its 82-degree field of view is slightly narrower than Pupil Core, but it still allows for comfortable head movements. However, it requires controlled lighting conditions for optimal performance. The proprietary software provides advanced analysis features, making it suitable for research and commercial applications. Tobii Pro Glasses 3 have been used in studies on visual attention and social interaction [13].
- **SR Research EyeLink II[5]:** This high-end system offers exceptional accuracy (up to 0.01 degrees) and a sampling rate of up to 500 Hz, making it the most precise option on the market. However, it requires controlled lighting and is very expensive, limiting its accessibility to well-funded research laboratories. EyeLink II has been extensively used in various research fields, including cognitive neuroscience, psychology, and linguistics [7].
- **ETVision Wearable Eye Tracker[6]:** This wearable eye tracking glasses offers high acccuracy (0.5 degrees) and a sampling rate of up to 180 Hz. The glasses can be equipped with an additional sun shield for very bright environments and a proprietary software is provided for data acquisition and analysis. The ETVision Wearable Eye Tracker can be used for gaze, pupillometry, saccade, and fixation data detection and has been used in children neuroscience studies [15].
- **EyeTech VT3 mini[7]:** This fixed compact and lightweight eye tracker offers good accuracy and a sampling rate of up to 200 Hz. Its wide field of view and robustness to varying light conditions make it suitable for real-world applications. The system comes with proprietary software for data analysis and visualization. EyeTech VT3 mini has been used in studies on reading and visual search [9].
- **Gazepoint GP3[8]:** This fixed affordable eye tracker offers decent accuracy and a sampling rate of up to 60 Hz. Its compact design and ease of use make it a popular choice for researchers and developers. The system comes with open-source software for data analysis and can be integrated with various programming languages. Gazepoint GP3 has been used in studies on human-computer interaction and usability [2].

As can be seen in Table 1, each system offers a unique combination of features and capabilities, catering to different needs and budgets. The Pupil Labs Pupil Core, with its open-source platform and affordability, is an attractive option for researchers and developers seeking flexibility and customization. The Tobii Pro Glasses 3, while more expensive, boasts advanced features and proprietary software that may be appealing to those requiring a comprehensive solution. The SR Research EyeLink II, with its exceptional accuracy and high sampling rate, is a top-tier choice for research laboratories with substantial funding. The ETVision

[4] https://www.tobii.com/products/eye-trackers/wearables/tobii-pro-glasses-3
[5] https://www.sr-research.com/eyelink-ii
[6] https://www.argusscience.com/ETVision.html
[7] https://imotions.com/products/hardware/eyetech-vt3-mini
[8] https://www.gazept.com/product/gazepoint-gp3-eye-tracker

Table 1. Comparison of Eye-Tracking Systems

System	Accuracy	Sampling Rate	Field of View	Illumination	Data Processing and Analysis	Cost and Accessibility
Pupil Labs Pupil Core	High (0.6°)	Up to 200 Hz	120 degrees	Robust to varying light conditions	Open-source software with extensive analysis tools	Relatively affordable, accessible to researchers and developers
Tobii Pro Glasses 3	High (0.6°)	Up to 100 Hz	82 degrees	Requires controlled lighting	Proprietary software with advanced analysis features	Expensive, primarily targeted towards research and commercial applications
SR Research EyeLink II	Very high (0.01°)	Up to 500 Hz	Varies depending on model	Requires controlled lighting	Proprietary software with comprehensive analysis tools	Very expensive, primarily used in research laboratories
ETVision Wearable Eye Tracker	High (0.5°)	Up to 180 Hz	-	Sun shield provided for very bright environments	Proprietary software for data acquisition and analysis	Expensive, primarily used for research scopes
EyeTech VT3 mini	High (0.5°)	Up to 200 Hz	Wide	Robust to varying light conditions	Proprietary software for data analysis and visualization	Relatively affordable
Gazepoint GP3	Good (0.5° to 1°)	Up to 60 Hz	-	-	Open source software for data analysis, various programming languages supported	Affordable

Wearable Eye Tracker offers high flexibility and adaptability together with a proprietary software that allows extensive data analysis. The EyeTech VT3 mini is a compact and lightweight eye tracker suitable for real-world applications due to its wide field of view and robustness to varying light conditions. The Gazepoint GP3 is an affordable and user-friendly eye tracker with decent accuracy and open-source software, making it a popular choice for researchers and developers.

Ultimately, the selection of the optimal eye-tracking sensor for the APURE project will depend on a careful evaluation of these characteristics in light of the project's specific requirements and constraints. By considering the trade-offs between performance, cost, and accessibility, the project team can make an informed decision that will pave the way for the development of a successful objective audiometer.

3 Sensor Selection for the APURE Project

Given the project's objectives and constraints, we selected a set of requirements to be met during the device selection phase. As reported in Table 2, the eye tracker system should have an accuracy of at most 0.8° to ensure precise tracking and measurement and it should operate at a sampling rate of at least 50 Hz to capture rapid eye movements and provide smooth pupil data streams. Moreover, an accessible software API is necessary for seamless integration with various software platforms and to enable interfacing with customized software modules. Another requirement is the real-time wireless operation, essential for preserving the user mobility and reducing tethering constraints. An additional advisable feature is incorporating multiple IR cameras per eye, enhancing pupil detection accuracy by providing multiple viewpoints, reducing occlusion and improving robustness. Lastly, maintaining a total cost below 15,000€ ensures the system is economically viable for the project budget. It should be noted that the use of a threshold in Table 2 rather than a specific price for each product is justified by the fact that costs vary according to the sector requesting the product (public, private or academic). In addition, for devices with proprietary software, the cost of the licensing plan must be added to the initial price of the product. The latter is not fixed as each brand offers a range of plans to choose from.

Under all the above conditions, the Tobii Pro Glasses 3 emerges as the most suitable eye-tracking device for the APURE project while the Pupil Labs Pupil Core, could be considered as the second most appropriate choice. These wearable systems offer a compelling combination of accuracy, usability, and affordability, aligning with the project's goals of developing an objective audiometer that is both effective and accessible.

The Tobii Pro Glasses 3 with its high accuracy (up to 0.6°), offers high precision and a sampling rate of up to 100 Hz, which is sufficient for capturing the relevant aspects of the pupil dilation response. The system's wider field of view (82 degrees) ensures user comfort and allows for natural head movements during audiometry testing. Although the Tobii Pro Glasses 3 requires controlled lighting conditions, this can be easily achieved in a clinical setting. The system's

Table 2. Eye trackers requirements matching for the APURE project

Requirement / Device	Accuracy ≤0.8°	Sampling Rate ≥50 Hz	Software API	Real-time wireless operation	Multiple IR camera per eye	Cost ≤15k€
Pupil Labs Pupil Core	✓	✓	✓			✓
Tobii Pro Glasses 3	✓	✓	✓	✓	✓	✓
SR Research Eye-Link II	✓	✓	✓			
ETVision Wearable Eye Tracker	✓	✓	✓	✓		
EyeTech VT3 mini	✓	✓	?			✓
Gazepoint GP3		✓	✓			✓

proprietary software provides advanced analysis features, which may be beneficial for in-depth investigation of the relationship between pupil response and auditory stimuli. The device, composed of the wearable glasses and a portable recording and wireless communicating unit, is shown in Figure 1. The Tobii Pro Glasses 3 have been widely adopted in research and commercial applications due to their ease of use and robust performance. The provided web API easily allows to both capture the live streaming of the four eye cameras, the world camera and the pupil processed data, as shown in Figure 2. For example, they have been used to study visual attention patterns in real-world scenarios, such as shopping behavior and driving performance [13]. The system's ability to capture natural eye movements in unconstrained environments makes it a valuable tool for understanding human behavior and cognition.

The Pupil Labs Pupil Core, with its high accuracy (up to 0.6°) and sampling rate (up to 200 Hz), ensures precise and reliable measurement of pupil size and reactivity. This level of precision is crucial for capturing the subtle changes in pupil dilation that may be indicative of hearing thresholds. Additionally, the system's robustness to varying light conditions makes it suitable for use in diverse clinical settings, where lighting conditions may not always be perfectly controlled. The open-source nature of the Pupil Core platform further enhances its appeal, as it allows for customization and integration with other software tools, facilitating the development of a tailored solution for the APURE project. The only drawbacks of this system is the need to be connected through a USB cable to be operated and the fact that employs only one IR camera per eye. Overall, the versatility and adaptability of the Pupil Core have been demonstrated in various research applications. For instance, it has been successfully employed to investigate the effects of cognitive load on pupil dilation during complex tasks, providing valuable insights into the relationship between cognitive processes and

Fig. 1. The Tobii Pro Glasses 3 kit, composed of the wearable glasses unit connected to a portable computing unit that provides storage and connectivity.

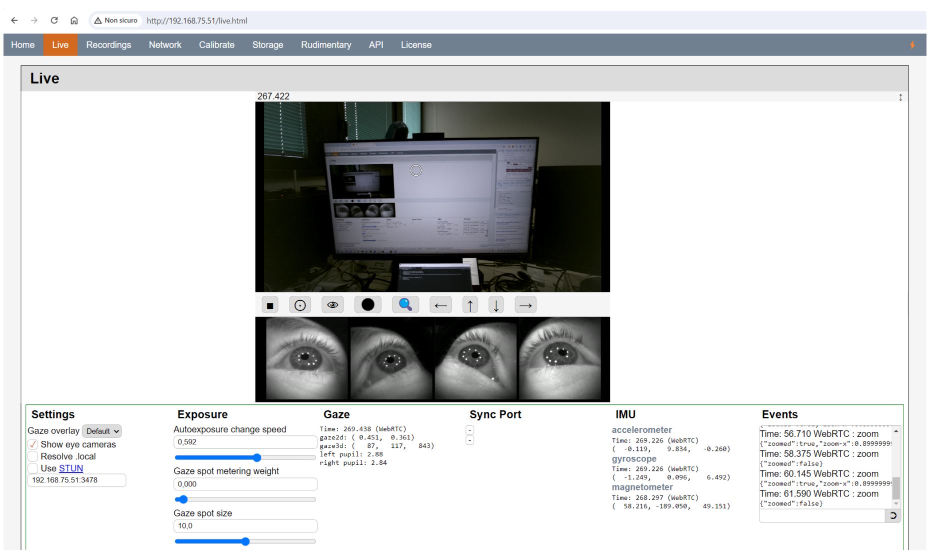

Fig. 2. Screenshot of the web API available through the glasses local WiFi hotspot providing real-time camera recording and sensors data streaming.

physiological responses [8]. Moreover, the Pupil Core's open-source nature has fostered a vibrant community of developers and researchers, contributing to a growing body of knowledge and resources for utilizing this technology in innovative ways.

While the SR Research EyeLink II boasts superior accuracy and sampling rate, its high cost and requirement for controlled lighting make it less suitable for the APURE project, which aims to develop an affordable and accessible audiometer for widespread clinical use. While the ETVision Wearable Eye Tracker might be interesting for the exposed features, its high cost make it not viable for the project. The EyeTech VT3 mini and Gazepoint GP3, while more affordable, do not offer the same level of accuracy and precision as the Pupil Core and Tobii Pro Glasses 3, which are essential for reliable audiometry results.

The choice between Tobii Pro Glasses 3 and Pupil Labs Pupil Core was guided by the specific priorities of the APURE project. Initially, we considered the Pupil Core for its cost effectiveness and open source flexibility. However, the advanced analysis functions and wider field of view of the Tobii Pro Glasses 3 were ultimately more critical to our analysis. Given the available funding, we decided to purchase and test the Tobii Pro Glasses 3.

4 Discussion and Conclusion

The convergence of IoT, ocular movement analysis and eye-tracking technology represents an interesting advancement, augmenting system capabilities and its applicability in different case study from healthcare to consumer behavior.

The real-time data acquisition and remote monitoring is facilitated by IoT enable responsiveness and adaptability in applications, in particular in the medical domain. Simultaneously, in market research, it allows for dynamic, data-driven strategy refinements.

In this paper we highlight the most promising eye tracker for clinical purpose available in the market. We try to highlight main features and characteristics of state-of-the-art technologies in this field, describing choices we made in our ongoing project. The Tobii Pro Glasses 3 and the Pupil Labs Pupil Core represent the most promising eye-tracking sensors for the APURE project. Their combination of accuracy, usability, and affordability aligns with the project's goals of developing an objective audiometer that is both effective and accessible. By leveraging these cutting-edge technologies, the APURE project can advance the field of audiology and improve the lives of individuals with hearing impairments.

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