An Overview of Technologies and Tools Using Eye Tracking in the Research of Architecture and Urban Spaces

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Abstract

The use of eye tracking technology in architectural research is innovative and allows for experiments to be conducted in the field of perception of the built environment in various aspects and scales. Designers are interested in improving the quality of proposed solutions in the field of interior design, wayfinding, and perception of the urban environment. The researcher wants to obtain measurable results that can indicate the direction of development of the proposed concepts based on the evaluation of existing solutions as well as those in the design phase. In order to effectively carry out experiments using the described technology, it is necessary to be familiar with the available research tools, techniques for conducting experiments, and the interpretation of results and their implementation in subsequent iterations of experiments or project implementations. Therefore, the author decided to prepare a review article on available technologies and research tools supported by eye tracking technology and its implementation in research in the field of architecture and urban planning. His own experience with attempts to use the tool made available for research in the form of THE EYE TRIBE with proprietary software written by professor Paweł Kasprowski (SUT - Department of Applied Computer Science, Faculty of Automation, Electronics and Computer Science), became a pretext for seeking answers to questions concerning the diversity of eye movement recorders available on the market and their integration with software for processing and interpreting observation data. The questions raised in the article concern the cost of purchasing the system, its ease of use, and the level of integration with popular virtual environment modeling tools used to simulate spaces designed by architects and researchers of built environment perception. The fundamental issue from the researcher's point of view is whether it is possible to design and launch a research station without specialist knowledge in disciplines other than the leading ones (architecture and urban planning). If not, who should be involved in the research team in order to achieve the expected results? The final conclusions include a description of the difficulties associated with the use of the tools described and recommendations on how to organize the process of preparing and conducting experiments/research.

Keywords: *eye tracking, architecture, perception, tools, technology*

1. Introduction

Eye tracking is an advanced research technology that is increasingly being used in architecture and related fields [1]. This method, developed over a century ago for the purposes of science such as psychology and medicine, has also found widespread application in economics and design sciences in recent years [1]. The main areas of application and research using eye tracking in architecture include activities such as architectural heritage management, research into historical architectural and urban space, 3D mapping in urban environments, and architectural education. Eye tracking serves as a pro-social tool for managing urban and architectural heritage [2]. It allows for the objectification of architectural decisions by studying the visual preferences of different social groups. By recording the eye movements of a large group of observers, it is possible to study the preferences that govern the perception process and observe changes in the way the architectural space is perceived [2]. An innovative direction is the use of eye tracking to study historical architectural space in the context of user perception [3]. This methodology enables an objective analysis of how contemporary users perceive, identify, and interpret architectural monuments and historical spaces. Eye tracking offers a variety of support for the architectural education of future designers [4]. This technology allows eye movements to be tracked during the analysis of architectural structures, enabling a better understanding of how professionals and non-professionals perceive these structures [4]. Eye tracking studies also help to analyse the level of acquisition of specialist professional skills [4].

Specialised applications of this technology enable research into trade fair stands and exhibition spaces. Eye tracking is used in research into trade fair stands, focusing on the overall design of the stands and their demonstration areas – zones where products or other exhibits are used to present a visual offer [5]. This method allows for the analysis of exhibitors' marketing activities using a mobile eye tracker [5]. The study of landscape architecture and public spaces using eye tracking technology is used to investigate landscape preferences [6]. Eye tracking experiments are increasingly used to analyse how respondents observe landscapes, although such studies are very time-consuming and costly [6]. An innovative approach to the described tool enables 3D mapping in urban environments by combining immersive technologies. Thanks to the possibility of incorporating virtual and augmented reality (VR and AR) into research, low-cost studies on the impact of changes made to existing spaces and testing of multi-variant solutions at an early design stage become available. The innovative approach combines eye tracking tools with 3D mapping to increase the interpretability of experiences in real outdoor urban environments [7]. Through videogrammetry, it is possible to reconstruct the position of the participant's head and then project the fixations measured using eye tracking [7]. Combined with VR/AR technologies, this technology opens up new possibilities in architecture [8]. The

integration of eye tracking with virtual reality goes beyond simple interaction, influencing areas such as architectural design, medical diagnostics, neuroscience research, and educational interventions [8]. Eye tracking technology offers a powerful, quantitative approach to assessing visibility, aesthetics, and design components [9]. It provides unique insights into visual engagement, which is crucial for understanding the impact of design elements on the user experience [9]. Visual perception studies enable the comparison and evaluation of differences in visual attention during the exposure of various architectural elements [10]. Advanced statistical techniques are used in the analysis of temporal characteristics of visual perception [10]. The developing technology of eye tracking is used in diagnosis and therapy, especially as an assistive technology tool (EGAT) in art therapy [11]. It enables relatively independent and autonomous creative activities, allowing for the expression of emotions and the revelation of skills [11]. Despite its great potential, the use of eye tracking in architecture faces certain limitations related to the use of devices [5]. The main challenges include:

- high research costs and time-consuming experiments [6] [13],
- the need for specialised equipment, software and knowledge [12],
- the need for adequate preparation of research procedures,
- interpretation of complex visual data.

Eye tracking in architecture represents an interdisciplinary approach combining technology, perception psychology, design and social sciences. The development of this field opens up new perspectives for a better understanding of human interaction with architectural space and may significantly influence future design practices. When implementing eye-tracking technology in projects, a number of technical, organisational and interpretative challenges must also be taken into account. The most important of these are [13] [14]:

- advanced eye-tracking devices and dedicated software are expensive, which can be a barrier for smaller design offices or investors with limited budgets,
- the complexity of data interpretation. Analysing and correctly understanding eye-tracking results requires specialist knowledge. The data is often complex, and its interpretation – especially in the context of three-dimensional spaces – can be difficult and time-consuming,
- limited representativeness of the sample. Eye-tracking studies are usually conducted on relatively small groups of users, which may limit the possibility of generalising the results to the entire population of future users of the interior,
- the influence of the test environment on the results. Tests conducted in laboratory or virtual conditions may not fully reflect the actual behaviour of users in the target space. Differences may result from the presence of other stimuli, such as sound, movement or the presence of other people,
- difficulties in integration with other data. Combining eye-tracking results with other analytical tools (e.g., surveys, EEG studies, heat maps) requires specialist know-how and can be time-consuming,
- technical and organisational challenges. The need to calibrate equipment, ensure the comfort of test subjects, and operate mobile devices in real interiors (e.g. glasses with cameras) requires additional resources and logistics [15].
- ethical and privacy issues. Recording eye movements and user behaviour requires informed consent and adequate protection of personal data.

In order to effectively implement eye tracking in interior design projects, it is worth planning research in advance, drawing on expert knowledge and combining different research methods to obtain a more complete picture of user behaviour [13].

2. Tools for interpreting and visualising results

There are many commercial and open source tools available that enable the analysis and presentation of eye tracking data in graphical form. These solutions support various forms of interpretation — from classic heatmaps and fixation paths to advanced behavioural analyses and integration with other signals (e.g. emotions, EEG). Popular tools such as Tobii Pro Lab and the libraries described below offer advanced data analysis capabilities, heatmap creation, gaze line charts, area of interest (AOI) statistics, and data export for further analysis. [16]. A free online tool for analysing and visualising eye movements, taking into account individual differences and data quality. It supports various output formats and generates interactive visualisations. [17]. This group includes, among others:

- Pupil Labs (Pupil Player, Pistol, GazeParser) – a set of open source tools for data processing and visualisation (video with eye tracking data superimposed on the image, heatmap export, 2D and 3D gaze direction analysis) [18] [19].
- PyTrack – a Python tool enabling comprehensive analysis, from parameter extraction to visualisation (including heatmaps, gaze trajectory charts) [20].
- GazeVisual-Lib - an open source library with a data repository, enabling detailed quantitative analysis and visualisation of eye tracking data quality (heatmaps, AOI charts, fixation paths) [21] [22].
- EyeTrace2014 - a modular tool that allows you to compare different fixation detection algorithms, visualize results and analyse data from different measuring devices [23].

The available forms of graphical presentation of data recorded during the experiments allow for the representation of:

- heatmaps – colourful visualization of attention intensity in specific areas of the stimulus [24] [16],
- scanpaths – eye movement paths with information about the order and duration of fixations,
- AOI analysis – statistics and visualizations focused on defined areas of interest on the stimulus,
- dynamic 3D visualizations – enable the interpretation of data from real or virtual 3D spaces [16],
- fusion with other signals (e.g. emotions) – tools enabling simultaneous analysis of eye tracking and, for example, physiology or facial expressions [24] [25].

Specialized solutions and the latest trends implemented within the Advanced Gaze Analytics Dashboard platform enable advanced visualization of gaze metrics in real time, analysis of cognitive processes and interactive data exploration [26]. Integration with VR/AR environments requires dedicated tools for eye tracking analysis in three-dimensional environments.

The tools listed in Table 1 allow for a wide range of analyses and effective presentation of results, supporting both scientific research and practical applications in UX, neuromarketing and education [28]. The above list provides an overview of popular and widely available online tools and methods for the graphical presentation and interpretation of eye-tracking research results, along with links to the manufacturers' websites.

Tab.1 Popular tools supporting research using eye tracking technology

Tool	Lecence type	Key features
Tobii Pro Lab	commercial	Heatmaps, scanpaths, AOI, data export
Gazepath	Open source	Eye tracking analysis, interactive visualisations
PyTrack	Open source	Heatmap analysis and visualisation, scanpath, parameters
GazeVisual-Lib	Open source	Heatmaps, comparative data quality analysis
EyeTrace	Open source	Various data analysis and visualisation algorithms
Pupil Player/Pistol [27]	Open source	Video analysis, 2D/3D gaze visualisation

3. VR headsets with eye tracking technology and open API

Currently VR headsets with eye tracking and open APIs are available on the market, allowing developers to integrate eye tracking technology into their own applications. In 2025, there are several consumer and professional solutions that offer these capabilities on the market. Models with open APIs include Meta Quest Pro, HTC Vive Pro Eye, Varjo Aero, and Pico 4 Enterprise. Meta Quest Pro is one of the most accessible consumer headsets equipped with eye tracking [29] [30], offering an average accuracy of 1.652° with a precision of 0.699° in a field of view of 15° [30]. Quest Pro supports integration with popular development environments and offers an API that allows access to eye tracking data [31] [32]. HTC Vive Pro Eye is a professional headset with a built-in eye tracking system from Tobii [33]. The device offers higher spatial precision compared to Meta Quest Pro [34]. Vive Pro Eye supports the SteamVR SDK and Tobii XR SDK [35], which provides flexibility in choosing a development platform. Varjo Aero is a professional-grade headset with the lowest eye tracking latency among commercially available devices, which, according to the manufacturer, is approximately 15–45 ms [35]. Varjo offers a dedicated SDK and is particularly popular in research applications [36] [37]. The Pico 4 Enterprise system is used in industrial and research projects with integration of eye tracking [38] [39]. The device offers an API for integration with Unreal Engine and other development platforms. Available Platforms and SDKs - OpenXR is a standard API for augmented reality applications that supports eye tracking as an extension [40]. This allows you to create applications compatible with different headsets without having to rewrite the code for each device. Unity and Unreal Engine Popular game engines offer support for eye tracking through dedicated packages and plugins [36] [37]. Unity works particularly well with the Tobii XR SDK, while Unreal Engine is used with various headsets in research projects. SteamVR The SteamVR API offers support for eye tracking in compatible headsets, enabling access to eye tracking data in VR applications [35].

4. Technical characteristics of available VR sets

The precision of modern VR headsets with eye tracking achieves an accuracy of 1-3° in the central part of the field of view [30] [33]. The accuracy decreases significantly in peripheral areas (>15°), which should be taken into account when designing applications. Another important feature of these systems is the sampling frequency. Most consumer devices offer a sampling frequency of 72-90 Hz [41], while professional systems can achieve higher values. Meta Quest Pro operates at a frequency of approximately 90 Hz [41]. In the implementation of eye tracking, the delay in eye movement registration is also important. It varies depending on the system and can range from 15 ms (Varjo) to 52 ms (other headsets) [35]. This is a key parameter for applications requiring real-time response. For comfortable use of headsets, the resolution of the displays is also important. From the point of view of architecture experiments, the wide viewing angle characteristic of panoramic headsets available for games and simulation environments may be significant. Unfortunately, such hardware sets often have limited access to the programming platform, which restricts the compatibility of such technical solutions with programs used in urban and architectural design and limits research applications without the involvement of the platform manufacturer. The tools and technologies that are being developed have a number of applications and limitations. The possibilities of eye tracking applications using virtual reality enable the implementation of advanced functions. Many of them are based on the ability to optimize the image generated by the graphics card based on the direction of gaze. Gaze-contingent rendering allows for the optimization of PC computing resources in terms of energy consumption, computing time, and quality improvement in the central area of the eye's field of vision. The technical limitations of the currently available technology include the following:

- decreased precision/accuracy in peripheral areas [42] [43],
- sensitivity to the position of the headset on the head (lower compared to mounting solutions under-monitor) [44],
- the need for calibration for optimal accuracy, as before,
- the impact of lighting on tracking quality (dark images – lower eye movement tracking precision).

5. Comparison of prices for eye tracker data analysis software and kits

The price range of eye-tracking equipment depends on the class of the device, the accuracy of recording, and its intended use. Budget models (e.g. Gazepoint GP3, Pupil Labs) can be purchased at prices ranging from approximately 700 to 2,000 USD. Gazepoint GP3 — considered one of the most affordable trackers for scientific research, it allows for basic analysis with satisfactory accuracy under controlled conditions. Mid-range models (EyeTribe before discontinuation, modern Pupil Labs with higher resolution) cost between 2,000 and 5,000 USD. Advanced stationary systems (e.g. Tobii Pro X3-120, SR Research EyeLink) can cost several times more, with prices depending on the configuration of the sets and ranging from 8,000 to as much as 20,000 USD. Professional systems offer very high precision and recording speed, analytical functions complete with dedicated software for statistical and graphical interpretation of the collected data, or as additional license options. A much cheaper alternative are integrated VR sets (e.g., HTC Vive Pro Eye, Varjo VR-2 Pro), which can be purchased in the price range from 1,000 to 6,000 USD.

The available software supporting data acquisition, evaluation and presentation can be divided into open source (e.g. PyTrack, GazeVisual-Lib, Pupil Player, EyeTrace2014, Gazepath) and paid applications. Free software developed by the research community is available under licenses such as GPL, MIT, etc. Commercial applications vary greatly in price. Tobii Pro Lab software can be purchased in the form of annual licenses ranging from approximately 2,000 to 6,000 USD (depending on the level of functionality: basic, full, with data export add-ons). 3. Other well-known products such as iMotions, SMI BeGaze, and SR Research Data Viewer are available in the range of 3,000 to 10,000 USD for a one-time or annual license, depending on the modules and support.

Tab. 2 Classification of sample solutions with cost breakdown

Type of solution	Price range	Examplesy	Comments
Basic open source	free	PyTrack, Gazepath, EyeTrace2014	Requires independent configuration
Budget eye tracker	700–2,000 USD	Gazepoint GP3, Pupil Labs Core	For basic research
Professional eye tracker	8,000–20,000 USD	Tobii Pro, EyeLink	For advanced research, fast acquisition
Commercial software license	2,000–10,000 USD per year/one-time fee	Tobii Pro Lab, iMotions, BeGaze	Extensive support and analysis
VR kits with eye tracking	1,000–6,000 USD	HTC Vive Pro Eye, Varjo VR-2 Pro	Integration with immersive simulations

Comments on the data in Table 2:

- the cheapest option is open source kits (customized or ready-made based on Pupil Labs, Gazepath), but their configuration requires programming knowledge,
- professional systems (e.g. Tobii, EyeLink) and their software are much more expensive, but offer high precision and support for advanced analytical functions,
- when choosing an option, consider the cost of both hardware and software, as well as any licenses for additional analytical modules.

The prices shown above are indicative for 2025 and may vary depending on the region, purchasing conditions, and manufacturer promotions [45]. Eye tracking technology in VR headsets is rapidly developing. Apple Vision Pro is setting new standards in this field, while other manufacturers continue to improve their solutions. The development of the OpenXR standard and the increased availability of SDKs make eye tracking integration easier for developers. The availability of open APIs, combined with increasing accuracy and decreasing latency, makes VR headsets with eye tracking an attractive option for both researchers and commercial application developers in architecture and related disciplines focused on the quality of the built environment and its perception by users.

6. Own experiences – initial experiments

In 2022/23 and 2024/25, two PBL projects were carried out at the WA PŚ, the subject matter of which was related to finding one's way around a hospital facility, using the example of the National Institute of Oncology (NIO) in Gliwice. The first topic focused on visual identification and indicating key locations on the route patients take to the mammography examination point. It was crucial to identify decision points related to changing direction and to propose solutions that facilitating the finding of information about the way to the examination point. The results of the interdisciplinary team of students' work were the preparation, with the participation of patients and hospital staff, of guidelines for the team of designers implementing a comprehensive visual identification system for the NIO institution. The second project initiated as a result of the cooperation with NIO aimed to conduct research on the possibilities of modern technological tools that support the spatial orientation of patients using AR applications for indoor navigation. The project planned to use AR (augmented reality) technology to obtain a flexible solution that would allow dynamic and intuitive guidance of the user within the building. The work carried out made it possible to define the essential features of a mobile application for user navigation within the hospital building, launch a test version of the tool, and conduct trials on site.

During work on the above-mentioned projects, the Matterport photogrammetric platform and video inventory using a Samsung Gear 360 camera were used. After collecting the materials, it became necessary to carry out work outside the hospital and assess both the existing condition of the facility in terms of graphic identification and the level of complexity in finding information and routes within the building. It was natural to attempt to use eye tracking technology. The research group's initial decisions were to use the existing equipment base at the University of Silesia and to borrow a Tobii set from one of the laboratories of the Faculty of Biomedical Engineering/Department of Biomechatronics at the Silesian University of Technology. After discussions on the implementation of the set, there was not enough time to master the new tools and incorporate them into the ongoing work on the project. During preparations for the implementation of the second project, thanks to the help of Professor Paweł Kasprowski, it was possible to borrow THE EYE TRIBE Development Kit together with proprietary software. The research station was set up at the Faculty of Automation and Control Engineering of the Silesian University of Technology. The preparatory work included connecting the TRACKER ruler and configuring the software installed on a PC. The station, located in the VR and AR laboratory of the Faculty of Automation and Control Engineering of the Silesian University of Technology, was equipped with a 24-inch monitor, which was suggested as the image source for the analysis of the prepared images. Sample images from the analysis of selected locations in the facility are illustrated in Fig. 1, Fig. 2 and Fig.3.

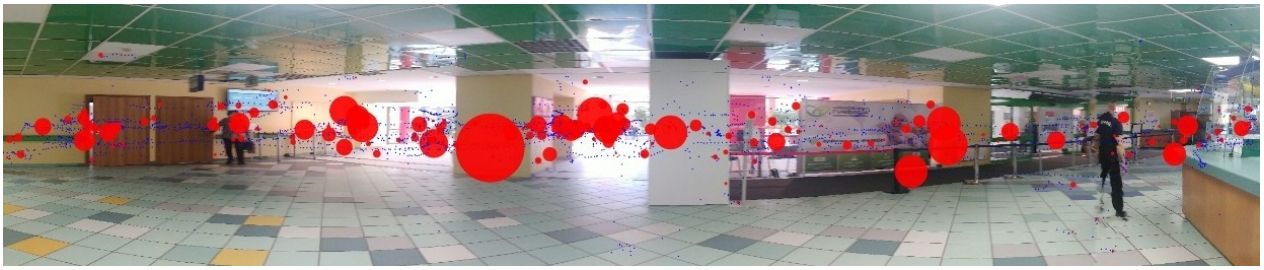

Fig. 1. An example of one of the test images used in the NIO experiment – fixation points (illustration by the author).

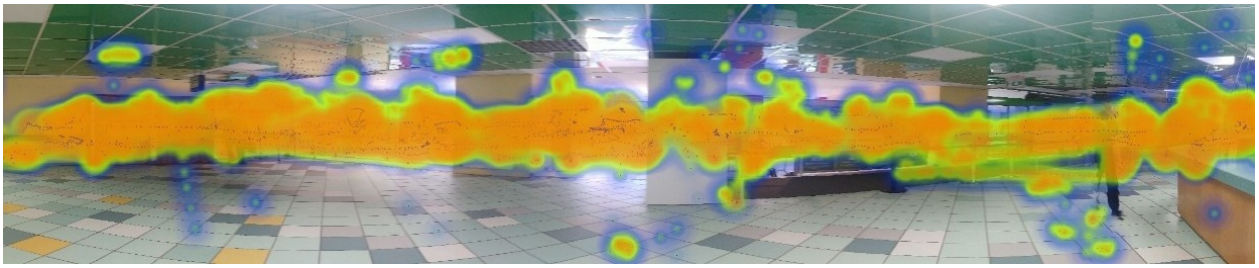

Fig. 2. An example of one of the test images used in the NIO experiment – hot map (illustration by the author).

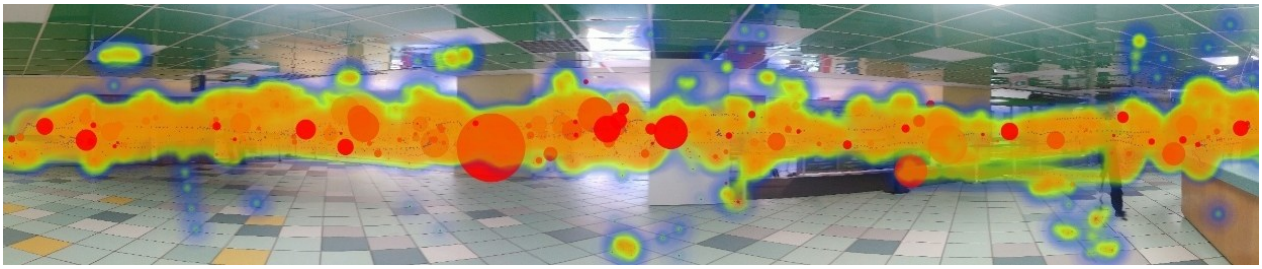

Fig. 3. A combination of information describing fixation points and a heat map enabling interpretation of the perception of space by a user visiting the NIO space for the first time (illustration by the author).

The research group consisted of two teams of students invited to participate in the experiment. The first group was represented by students familiar with the building and the route to selected locations in the NIO building. The second group of students had never been to the hospital premises and saw selected fragments of corridors on a computer screen for the first time. The photos presented were cropped for the purposes of the experiment and showed decision points important to the researchers on the way between the entrance to the building and the registration point and mammography examination rooms. The main aim of the experiment was to test the technology, master the research station and prepare it for effective work with a group of students. During the work, it turned out that many factors negatively affect the effectiveness of researchers' work with the eye-tracking device. The initial calibration of the device was a very important part of the entire process of preparing for the experiment. Many problems were encountered that required:

- improving the participant's position in relation to the screen and the eye movement recording ruler. This was achieved by moving the chair on which the person was sitting to the edge of the desk on which the monitor, cable and controllers in the form of a keyboard and mouse were located.
- it was also necessary to adjust the height of the ruler itself relative to the bottom edge of the monitor to the height at which the eyes of the participant were located.
- disturbances were also introduced by the glasses worn by the participants and the frequency of blinking.

First it was crucial to position the workstation in relation to the person being analysed. During the work, it was essential to block out natural light by closing the blinds and turning on diffused artificial ceiling lighting, which improved the quality of calibration. During calibration, it was also crucial to remove all objects behind the monitor on which the control images were displayed. It was also important that the participants in the experiment were able to correctly interpret the commands and instructions given by the person representing the research group. In order to carry out the commands that appear on the computer screen during the analysis of individual images, a series of actions were necessary using the computer keyboard and mouse. During subsequent trials, the operator, the person organizing the experiment, took control of some of the tasks performed using the keyboard in order to reduce the number of events involving looking away from the screen towards the keyboard in order for the participant to confirm the correctness of the key selection changing the images. The condition and concentration level of the participants in the experiment were also very important.

7. Conclusions and summary

The experiments allowed participants to familiarize themselves with the technology and equipment, as well as the objective difficulties associated with conducting the experiments. The conclusions from the work carried out indicate the need to eliminate the existing difficulties, which can be achieved through the use of advanced and costly technical solutions, such as Tobii glasses for recording images on an object with the superimposition of eye movements on the video image and the interpretation of results using dedicated software. An alternative is to build a new research station using augmented/mixed reality goggles for work generated in a virtualization environment or for the analysis of existing objects during their inspection. The second solution is much more complex, but cheaper to implement. Thanks to the support of doctoral students from the Faculty of Automation and Computer Science at the Silesian University of Technology, it is possible to prepare appropriate scripts based on an open SDK environment and integrate the equipment with available tools for visualizing and interpreting the results obtained. The planned work will allow for the preparation of purchases and the planning of further experiments in the field of analysing the perception of the environment built by professionals and users of public spaces and city residents.

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