

EVALUATION OF THE USABILITY OF WEB SERVICES WITH INTERACTIVE MAPS

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Abstract. The aim of this study was to evaluate the usability of web services incorporating interactive maps. The research combined objective eye-tracking analysis with subjective user assessments in a two-stage experiment involving 31 participants. The participants completed a series of tasks using five variants of a university campus map, grouped into three categories: a 3D Map, Street View maps, and Leaflet maps. Quantitative results indicated that 2D maps demonstrated higher cognitive efficiency and intuitiveness, reflected in shorter fixation times and more structured visual search patterns. In contrast, survey findings revealed that the 3D map achieved significantly higher levels of perceived satisfaction and overall user appeal. The discrepancy between objective performance and subjective preference highlights the importance of balancing functional efficiency with visual attractiveness in the design of interactive web maps. The findings provide practical guidelines for developing more usable and user-centered web services featuring interactive cartographic interfaces.

Keywords: interactive map; usability; eye-tracking

OCENA UŻYTECZNOŚCI SERWISÓW INTERNETOWYCH ZAWIERAJĄCYCH MAPY INTERAKTYWNE

Streszczenie. Celem tego badania była ocena użyteczności usług sieciowych zawierających interaktywne mapy. Badania łączyły obiektywną analizę śledzenia ruchu galek ocznych z subiektywnymi ocenami użytkowników w dwuetapowym eksperymencie z udziałem 31 uczestników. Użytkownicy wykonywali serię zadań, korzystając z pięciu wariantów mapy kampusu uniwersyteckiego, pogrupowanych w trzy kategorie: mapa 3D, mapy 2D Street View i mapy 2D Leaflet. Wyniki ilościowe wskazały, że mapy 2D wykazały wyższą sprawność poznawczą i intuicyjność, co znalazło odzwierciedlenie w krótszym czasie fiksacji i bardziej ustrukturyzowanych wzorcach wyszukiwania wizualnego. Z kolei wyniki ankiety ujawniły, że mapa 3D osiągnęła znacznie wyższy poziom odczuwanej satysfakcji i ogólnej atrakcyjności dla użytkownika. Rozbieżność między obiektywną wydajnością a subiektywnymi preferencjami podkreśla znaczenie zrównoważenia wydajności funkcjonalnej z atrakcyjnością wizualną w projektowaniu interaktywnych map internetowych. Odkrycia dostarczają praktycznych wskazówek dotyczących tworzenia bardziej użytecznych i zorientowanych na użytkownika usług sieciowych, wyposażonych w interaktywne interfejsy kartograficzne.

Słowa kluczowe: mapy interaktywne; użyteczność; eye-tracking

Introduction

Interactive online maps have become an integral part of web applications, finding use in navigation, spatial data analysis, and engaging storytelling. Their popularity stems from the ability to present complex geographic information in an attractively visual, dynamic, and user-friendly way. However, the effectiveness of these tools primarily depends on their usability and accessibility, as improper design can create barriers for users resulting in difficulties achieving desired outcomes. Ensuring that these tools are intuitive is crucial for delivering optimal user experiences.

The growing interest in interactive online maps increases the demand for their detailed evaluation in terms of usability and accessibility. These aspects are essential for users, particularly those with various types of impairments who often face challenges when interacting with digital platforms. Adhering to universal design principles and complying with commonly accepted web content accessibility standards can primarily enhance the usability and accessibility of a service, which in turn can lead to increased user satisfaction.

The study employed a combination of eye-tracking technology and a user experience survey. This approach enables the analysis of both actual user behaviour and subjective impressions. Such a method allows for a more comprehensive understanding of the user experience, combining quantitative and qualitative data. Moreover, it shows how different interactive maps are compared in terms of usability, indicating best design practices for such services and identifying areas that require improvement.

For the purposes of the study, a dedicated test application was developed, containing three types of interactive maps of the Lublin University of Technology campus. The first is a 3D map enhanced with a legend and interactive areas on buildings. The second, a 2D map with StreetView, was presented in two versions: one with the campus area highlighted (the remaining area greyed out) and one without this marking. The third map was created using the Leaflet library, also in two variants – differing in the amount and density of presented data. These maps were supplemented with legends and group markers. The differences

between the maps concerned not only spatial dimension (2D vs. 3D) but also the method and level of detail in the information presented.

This study aims to analyse the usability and accessibility of web services containing interactive maps by evaluating the intuitiveness of the interface, ease of navigation, clarity of information, as well as satisfaction, memorability, and learning speed of using the interface. Considering these aspects allows for a comprehensive assessment of the quality of user experience, encompassing both functional and cognitive elements. The obtained results aim to provide practical design guidelines for creators of such solutions, supporting the development of accessible, universal, and user-oriented map interfaces.

1. Related works

Interactive online maps play an increasingly important role in various fields, enabling the visualization and analysis of spatial data in an attractive and engaging way. For an effective user experience, key aspects include accessibility, usability, and the visual appeal of the interface. Scientific literature addresses heuristics, usability testing, user-centred design, and advanced visual techniques.

In the context of heuristics, Marquez, Meirelles, and Da Silva [12] proposed a dedicated set of usability assessment principles for maps, integrating cartographic standards. Salgado and Freire [7] emphasized the need to adapt Nielsen's classical heuristics to the specifics of mobile interfaces, which can also be extended to map interfaces.

Usability research focuses on optimizing interaction. De Jesus, Brito, and Fernandes [6] identified usability issues in the Geobahia maps, highlighting the need to simplify navigation. Popplin [16], in the context of the PPGIS platform, emphasized the importance of an intuitive interface, especially for new users. Çöltekin et al. [4] used eye-tracking to identify cognitively challenging areas of maps. Dong et al. [8] demonstrated the influence of visual elements (e.g., curvature and colour gradients) on task accuracy and completion time. Cybulski and Horbiński [5] compared the interfaces of Google Maps and OpenStreetMap, pointing



out the impact of the interface element layout on user efficiency. Popelka, Burian, and Belková [15] compared interaction methods, showing that panning works better for simple tasks, while multiple displays are more effective for complex analyses.

In the user-centered design stream, Roth, Ross, and MacEachren [18] in the GeoVISTA CrimeViz project demonstrated the value of an iterative approach and constant user feedback collection. Maiellaro and Verasano [11] showed that the integration of filters and visualization tools increases satisfaction and the effectiveness of data exploration in the context of cultural heritage.

Comparative studies on mapping APIs were conducted by Velkoski, Gusve, and Ristov [19], highlighting the flexibility of open-source libraries (Leaflet, OpenLayers) compared to the limitations of commercial APIs. Król [10] compared, among others, Bing Maps and jQuery CraftMap, demonstrating that simpler tools are initially more user-friendly but less functional. Chen and Li [3] proved that a windowed interface supports better performance in mobile navigation. Oberoi et al. [14] presented DesignWebs as an effective tool for exploring documents using concept maps.

Specialized use cases include studies by Brock et al. [2], who showed that audio-tactile maps improve the effectiveness and satisfaction of visually impaired users. Nivala and Sarjakoski [13] pointed to interdisciplinary challenges in map usability engineering. Jokinen [9] studied user preferences in navigation systems, demonstrating the superiority of touch interaction over voice. Portales et al. [17] developed SeMap – an application for exploring museum collections.

In terms of advanced visual techniques, Zhao and Shneiderman [20] presented YMap – a pixel-based tool with lower response times and smaller data transfers than vector systems. Gl. and Nv. Andrienko [1] developed the Descartes system, which facilitates map use for people without cartographic experience by automating mapping processes.

In summary, there is a wide range of approaches to analysing the usability of interactive maps. Their effectiveness depends on thoughtful design tailored to the needs of different user groups and usage contexts.

2. The aim and scope of the study

The aim of this study is to analyse and, consequently, evaluate the usability and accessibility of interactive maps integrated into web services. The research will focus on identifying and assessing key aspects such as interface accessibility, ease of navigation, clarity of information, and user satisfaction during interaction with interactive maps embedded in a test application.

The scope of the study includes: a literature review, the design of a test application, the preparation and execution of a study using an eye-tracker and a questionnaire, analysis of the results, and hypothesis verification.

The authors proposed two research hypotheses:

- H1.** A web service featuring a static 3D map demonstrates higher usability (simplicity, intuitiveness, and efficiency) than a web service featuring an interactive 2D map.
- H2.** A web service featuring a static 3D map, offering enhanced visualization of details and despite lacking interaction, provides a higher level of user satisfaction than an interactive 2D map offering interaction capabilities.

3. Research methodology

The research methodology constitutes a key element of this study, enabling the collection of data and the analysis of user interactions with interactive maps in the application developed by the research team.

A dedicated web application was developed for the purpose of the study, serving as the main environment for preparing and managing the five map variants used in the experiment. The application was built in React library, with interactive map views implemented using the Leaflet library and custom compo-

nents for markers, pop-ups, and map legends. It included different map configurations corresponding to the experimental conditions (M1–M5), with options to adjust visual layers, highlight areas, and present campus boundaries. During the survey phase, participants had access to the interactive version of the application, allowing them to freely explore the map variants. In contrast, during the eye-tracking experiment, participants were shown static screenshots of the respective maps to ensure controlled and consistent stimuli presentation.

Two complementary methods were used to conduct the research: eye-tracking and a user survey. The research process was divided into several stages. First, a web application was developed containing interactive maps of Lublin University of Technology campus, which served as the main subject of analysis. Then, tasks were prepared for the study participants, allowing the evaluation of interface usage and the recording of gaze patterns using eye-tracking. In the second part of the study, participants were asked to complete questionnaires aimed at collecting subjective opinions regarding usability, intuitiveness, memorability, and satisfaction with the use of interactive maps.

The collected data underwent verification and both quantitative and qualitative analysis, which enabled a comprehensive assessment of the effectiveness of the studied interfaces. The analysis utilized statistical summaries of the results obtained through eye-tracking (e.g., time to first fixation, number of fixations, time spent looking at areas of interest, number of saccades), as well as evaluations from the user questionnaires. This approach enabled a multi-dimensional assessment of the analysed maps, combining the objective dimension (related to user behaviour) with subjective perceptions. The selection of research methods and analytical tools was tailored to the aim of the study and enabled a reliable verification of the proposed research hypotheses.

3.1. Research group

The study involved 31 participants, including 5 women and 26 men, all of whom were Computer Science students at the Faculty of Electrical Engineering and Computer Science of Lublin University of Technology. Prior to the start of the experiment, a brief introductory interview was conducted, which revealed that most participants had prior experience with web services containing interactive maps.

3.2. Research setup

The experiment was conducted in a laboratory at the Faculty of Electrical Engineering and Computer Science of Lublin University of Technology, where the research conditions were carefully prepared to minimize the influence of external factors. The room had consistent lighting conditions, with windows covered and artificial lighting turned on. Each research session was conducted in the presence of two individuals: the participant and the person responsible for overseeing the entire experiment. The participant sat on an adjustable chair, allowing for height modification and comfortable positioning.

The research setup consisted of a Gazepoint GP3 HD eye tracker and an Acer Nitro 5 laptop equipped with an AMD Ryzen 7 5800H processor, 32 GB DDR4 RAM, a dedicated NVIDIA GeForce 3060 graphics card, a 512 GB SSD, and a 15.6-inch screen with a resolution of 1920×1080. The system ran on Windows 10 with Gazepoint Control and iMotions 9.0 software. The Gazepoint GP3 HD is an eye tracker enabling precise tracking of eye movements, operating at a sampling rate of 150 Hz, and providing measurement accuracy within the range of 0.5 to 1 degree. The optimal distance between the participant and the eye tracker was about 65 cm and was maintained throughout the entire experiment. The device itself was centrally placed just below the laptop screen, ensuring stable positioning and providing comfortable measurement conditions during each research session.

The Gazeport Control software was responsible for recording eye movements, while iMotions 9.0 was used for conducting the study, calibrating the device, and analysing the collected results. After the experiment, the data were presented in the form of heatmaps, fixation paths, and tables containing detailed information on eye-tracking parameters.

3.3. Eye-tracking study

The aim of the eye-tracking study was to examine user reaction times, task performance effectiveness, and user behaviour during interaction with the interactive map of the Lublin University of Technology campus. The experiment was designed to collect objective data in the form of the number of fixations, fixation durations, time to first fixation on the target map object, as well as the accuracy and effectiveness of task completion.

Before beginning the experiment, basic participant information such as gender and age was collected. Each participant began the study with eye-tracker calibration, and upon completion, proceeded to carry out the tasks. Instructions were displayed sequentially – the participant first read the task description, followed by the appropriate map view. After locating the correct object, the user confirmed their selection and moved on to the next instruction.

The study involved five different types of maps, differing in their information presentation style:

- M1: 3D map of the campus from the Lublin University of Technology website,
- M2: 2D map with StreetView and designated campus area,
- M3: 2D map with StreetView without a designated campus area,
- M4: 2D map from the Leaflet library with a designated campus area and all elements enabled,
- M5: 2D map from the Leaflet library with a designated campus area and selected elements enabled.

An additional difference between the analysed maps was their spatial orientation. The 3D map (M1) was presented in an isometric perspective and positioned to facilitate orientation on the campus in relation to Nadbystrzycka Street. Along this street are located the main buildings of Lublin University of Technology, making it a natural point of reference for most staff and students. In contrast, the 2D maps (M2–M5) were oriented to the north, in accordance with standard cartographic conventions, which resulted from the limitations of the StreetView technology and the Leaflet library. This difference was a consequence of both the characteristics of the mapping tools used and the intended method of data presentation.

The experiment consisted of four research scenarios (Table 1), applied to each of the five map types. Each scenario involved locating an object on the map – a building of Lublin University of Technology. The building names were familiar to the study participants.

Table 1. Task descriptions

Task No.	Task description
1	Find the building that houses the Department of Computer Science ("Pentagon").
2	Find the Innovation and Advanced Technology Center ("Rdzewiak").
3	Find the Rector's Office building.
4	Find the Faculty of Electrical Engineering and Computer Science (WEII) building.

The tasks were designed to assess the speed and accuracy of locating buildings, the memorability of the interface, and the intuitiveness of map usage by recording eye movements and analysing fixation patterns. The study results also provided valuable insights into possible user interface improvements, which may contribute to enhanced intuitiveness and functionality.

3.4. Survey research

Following the experiment, participants were asked to complete a survey to evaluate the usability, satisfaction and memorability of the Lublin University of Technology's interactive campus map. The questionnaire was based on questions adapted from the SUS (System Usability Scale) and PSSUQ (Post-Study System Usability Questionnaire), along with several additional questions proposed by the authors to address the specific context of the study. Consequently, the survey consisted of 12 questions. Participants rated each question using a 5-point Likert scale, where: 1 – Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree and 5 – Strongly Agree.

Table 2. Survey questions

No.	Questions
1	The map is visually appealing.
2	Information on the map is presented in a clear and understandable way.
3	The colour scheme of the map is pleasant and easy on the eyes.
4	The interactive map captures my interest and encourages exploration.
5	The interactive map is intuitive and easy to use.
6	The features of the interactive map are easily accessible.
7	Learning how to use the interactive map is quick and easy.
8	I feel confident using the interactive map.
9	The interactive map helps me easily remember the locations of campus buildings.
10	Highlighting a specific campus area makes the map easier to use.
11	Aligning the map with a main street as a reference point is intuitive and helpful for orientation.
12	I prefer a 3D map over a 2D map

For a more detailed analysis, the questions were grouped into three categories: usability, satisfaction and memorability. Each question in a category was given a weight according to its importance in the evaluation of the interface, as shown below:

- usability (questions 2, 5, 6, 7, 8, 10, 11) – weight: 2,
- satisfaction (questions 1, 3, 4, 12) – weight: 1.5,
- memorability (question 9) – weight: 1.

A total score for each interface was calculated based on both the number of positive responses and the assigned weights of the individual questions. This approach allowed for the determination of a comprehensive usability index for each interface. This index was calculated using the following formula:

$$P = \sum_{i=1}^n (O_i \cdot W_i)$$

where P – total interface score, O_i – response value for question (Likert scale 1–5), W_i – weight assigned to question, n – total number of questions.

The maximum possible score an interface could achieve based on the survey responses was 105 points. This value was obtained by summing the products of the highest possible rating (5 points) and the corresponding weight assigned to each question.

4. Result of studies

4.1. Analysis of quantitative eye-tracking data

The study was conducted using five variants of campus maps, which were categorized into three groups: 3D Map (including only map M1), Street View Maps (including maps M2 and M3), and Leaflet Maps (including maps M4 and M5). The eyetracking analysis focused on key quantitative metrics: time to first fixation (TTFF), number of fixations (FC), number of saccades (SC), and total time spent within predefined areas of interest (DT).

Analysis of the average times to first fixation (Figure 1) revealed that the map M5 had the shortest mean time to first fixation in areas of interest, indicating greater cognitive efficiency

and higher visual intuitiveness. In contrast, the longest average time to first fixations was observed for the map M1, which may reflect its increased spatial complexity and the users' difficulty in quickly identifying relevant elements.

Map M1 also produced the highest average number of fixations (Figure 2), suggesting greater cognitive effort and more extensive visual exploration.

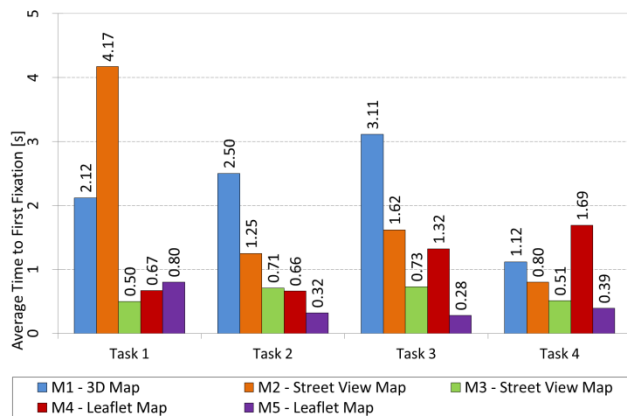


Fig. 1. Comparison of average times to first fixation (TTF) for all maps

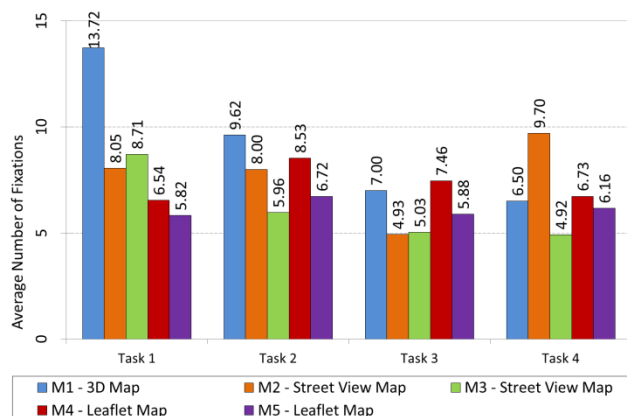


Fig. 2. Comparison of the average number of fixations (FC) for all maps

Saccade movements analysis revealed that maps M3 and M5 were associated with a lower average number of saccades (Figure 3), which may indicate a smoother and more focused visual navigation. In contrast, the M1 map recorded a higher number of saccades, suggesting greater difficulty in spatial orientation and a more disorganized search pattern when locating information.

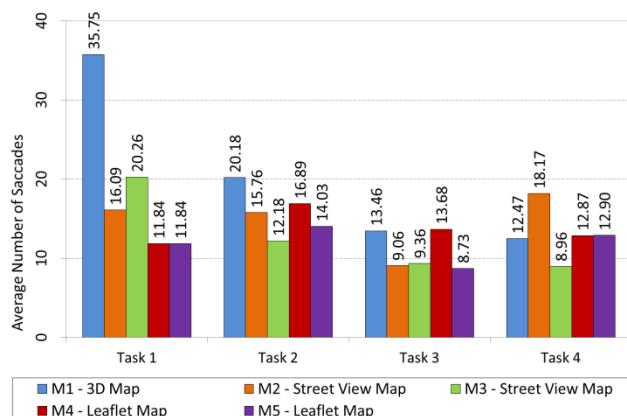


Fig. 3. Comparison of the average numbers of saccades (SC) for all maps

Analysis of dwell time (Figure 4) showed that M1 map was associated with longer average time spent looking at AOI across all tasks. These extended durations suggest that users required more processing effort when interpreting visual

information, possibly due to map complexity. In contrast, the shorter observation periods for maps M2 and M4 indicate greater visual intuitiveness and more efficient processing, enabling users to identify elements faster.

Figure 5 presents the distribution of eye-tracking metrics across the three map types: 3D Map, Street View Maps, and Leaflet Maps. The boxplots illustrate medians, interquartile ranges, mean values (marked with black crosses), and outliers for TTFF, FC, SC, and DT. As shown in Figure 5, noticeable differences between map formats are particularly evident in the temporal measures (TTFF and DT), with the 3D Map condition exhibiting distinct distributional patterns compared to the other two map types.

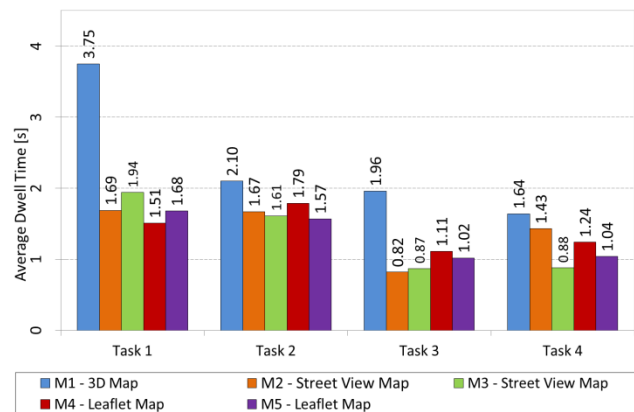


Fig. 4. Comparison of the average dwell times (DT) in all map

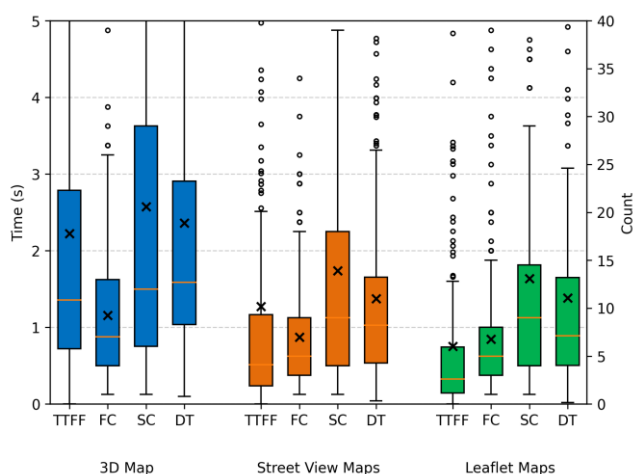


Fig. 5. Boxplots of eye-tracking metrics (TTFF, FC, SC, and DT) across three map types (3D Map, Street View Maps, and Leaflet Maps)

Because the assumption of normality was violated for all dependent variables (Shapiro–Wilk tests, $p < 0.05$), non-parametric analyses were conducted. Group differences among the three map types (3D Map, Street View Maps, and Leaflet Maps) were examined using the Kruskal–Wallis test. Effect sizes were calculated using epsilon-squared (ϵ^2).

Significant differences were observed for all four eye-tracking metrics (Table 3). The largest effect size was found for TTFF, indicating a strong influence of map type on time to first fixation. A moderate effect was observed for DT, whereas FC and SC showed small effect sizes.

Table 3. Statistical results

Metric	H	p-value	Effect size (ϵ^2)	Significant post-hoc differences
TTFF	88.08	< 0.001	0.34	All pairs differ
FC	8.40	0.015	0.03	3D Map vs Leaflet Maps
SC	10.82	0.004	0.04	3D Map vs Street View 3D Map vs Leaflet Maps
DT	40.39	< 0.001	0.15	3D Map vs Street View 3D Map vs Leaflet Maps

Post-hoc pairwise comparisons were performed using Mann-Whitney U tests with Bonferroni correction ($\alpha = 0.017$). For TTFF, all three map types differed significantly from each other ($p < 0.001$). For DT and SC, the 3D Map differed significantly from both Street View Maps and Leaflet Maps, whereas no significant difference was found between Street View Maps and Leaflet Maps. For FC, a significant difference was observed only between 3D Map and Leaflet Maps.

Overall, the results indicate that the 3D Map condition systematically differs from the other two visualization types, particularly in temporal eye-tracking measures (TTFF and DT), suggesting distinct visual processing patterns across map types.

4.2. Analysis of qualitative eye-tracking data

The heat maps revealed the interface areas that drew the most visual attention from participants. Red zones indicated the highest concentration of gaze, yellow denoted moderate interest, and green represented areas of minimal attention. The analysis demonstrated that interfaces with a high density of visual information (Figures 6, 7 and 9) resulted in more dispersed viewing patterns, whereas simplified map versions (e.g., Figures 8 and 10) produced more focused gaze areas, suggesting improved readability. Notably, in Figures 6 and 9, participants actively used the available legend when searching for specific objects, highlighting the importance of supplementary informational elements to support effective map navigation.

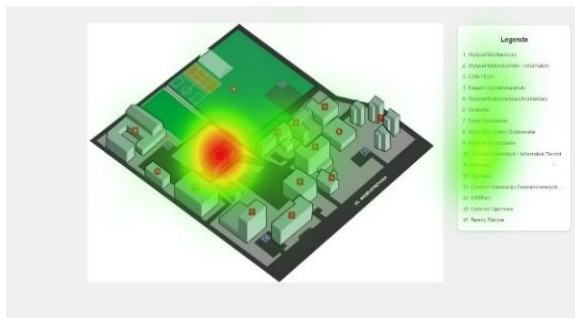


Fig. 6. Heat map for Task 3 on Map M1



Fig. 7. Heat map for Task 2 on Map M2

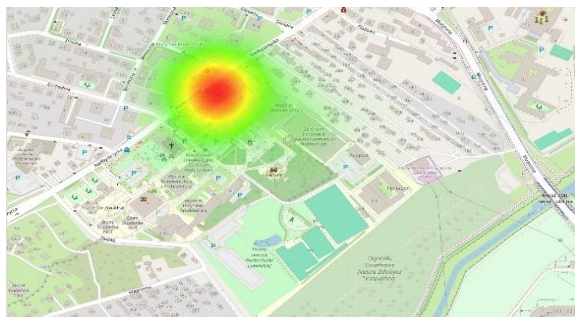


Fig. 8. Heat map for Task 4 on Map M3

The analysis of fixation paths enabled the observation of the sequence and structure in which participants directed their gaze across the maps. In the more complex map variants

(Figures 11–13), participants exhibited longer and more erratic gaze trajectories, which may suggest challenges in efficiently locating target buildings. In contrast, the simplified map versions (e.g., Figure 14) generated shorter, more structured gaze paths, indicating a higher level of interface intuitiveness.



Fig. 9. Heat map for Task 4 on Map M4



Fig. 10. Heat map for Task 4 on Map M5

Figure 11 illustrates a representative scan path recorded for the M1 map. The participant initially attempted to locate the target building independently by exploring the map, but subsequently directed attention to the legend located on the right-hand side. Before confirming the building's location, the participant cross-checked the information against the legend to ensure accuracy.



Fig. 11. Scanning path for Task 3 on Map M1



Fig. 12. Scanning path for Task 3 on Map M2

Figure 12 shows the execution of the task 3 for map M2. The respondent's eye activity appears dispersed across the entire campus area, revealing a search pattern: from the bottom of the map, towards the centre and the northern part of the campus. Through-out the task, the participant performed

several long saccades between distant locations on the map, suggesting a deliberate and goal-oriented search for specific buildings rather than random or chaotic exploration.

For the M4 map, Figure 13 illustrates a representative scan path characterized by a complex visual pattern involving two areas: the central part of the campus and the interactive map legend. The long saccades between these regions indicate an active comparison of information across both elements. The path shows a methodical approach to the task, with a clear pattern of attention between map content and interface controls, suggesting a strategic use of available resources to complete the task effectively.

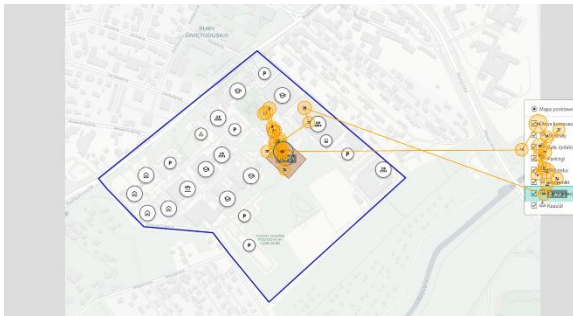


Fig. 13. Scanning path for Task 3 on Map M4

Figure 14 shows the scan path recorded for the M5 map. The participant's eye activity was concentrated in the central region of the campus, with a focus on two specific areas. He shuffled his gaze between these two map elements, completely ignoring the menu on the right. He ended his scan on an object that was not the target of his search.

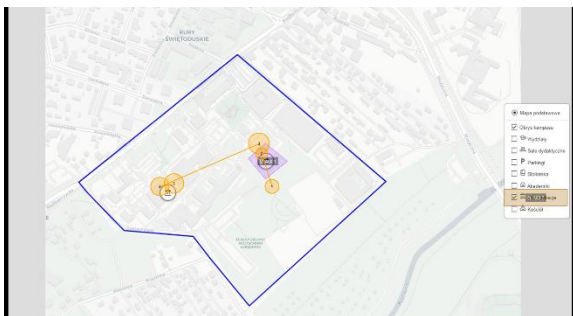


Fig. 14. Scanning path for Task 3 on Map M5

4.3. Analysis of survey results

In the survey, participants evaluated three groups of maps: the 3D map (M1), the Street View Maps (M2 and M3), and the Leaflet-based Maps (M4 and M5). Although the 3D Map (M1) performed weakly results in objective eye-tracking metrics, it received the highest overall rating in the user survey, scoring the 90.9% of points (Figure 15), as well as the highest usability and satisfaction index (Table 4). These results highlighting the strong influence of visual attractiveness and interactivity on users' subjective perceptions of the interface.

In contrast, maps based on the Leaflet library maps (M4 and M5), despite demonstrating superior efficiency in terms of cognitive performance, were rated less favourably by participant. This discrepancy between objective performance and subjective preference emphasizes the need to balance functionality with aesthetic and experiential aspects in the design of interactive web maps.

A statistical analysis was conducted to examine differences among three map types (Table 5). Due to violations of the assumptions of normality and homogeneity of variances, the Kruskal-Wallis test was applied. The analysis revealed significant differences between map types, $H(2) = 44.80$, $p < 0.001$, $\epsilon^2 = 0.49$, indicating a very large effect size. Post-hoc analysis

(Mann-Whitney U tests with Bonferroni correction, $\alpha = 0.017$) showed that 3D Map differed significantly from both Leaflet Maps and Street View Maps, whereas no significant difference was found between Leaflet Maps and Street View Maps.

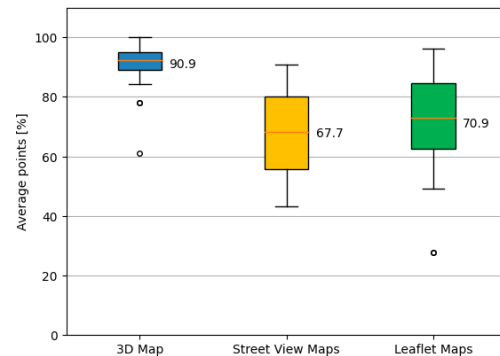


Fig. 15. Average number of survey points for each map

Table 4. Usability, satisfaction and memorability ratio for each map

	3D Map	Street View Maps	Leaflet Maps
Usability	3.98	3.14	3.52
Satisfaction	3.84	3.04	2.94
Memorability	3.77	2.83	2.63

Table 5. Post-hoc analysis results

Comparison	U	p	Significant
3D Map vs Leaflet Maps	821.5	< 0.001	***
3D Map vs Street View Maps	853.0	< 0.001	***
Leaflet Maps vs Street View Maps	527.5	0.255	ns

5. Conclusions

The aim of this study was to evaluate the usability of web services containing interactive campus maps by combining objective eye-tracking measurements with subjective user assessments. To achieve this goal, a dedicated web application featuring five map variants grouped into three categories (3D Map, Street View Maps, and Leaflet Maps) was developed and tested with 31 participants. The study analysed key performance metrics such as time to first fixation, fixation count, saccade count, and dwell time, alongside survey-based evaluations of usability, satisfaction, and memorability. The integrated methodological approach enabled a comprehensive comparison of cognitive efficiency and perceived user experience across different map formats.

The results of both the eye-tracking analysis and the survey study provide a nuanced understanding of the usability and user experience associated with different map types. The boxplot distributions and non-parametric statistical analyses demonstrated significant differences among the three map formats in all key eye-tracking metrics (TTFF, FC, SC, and DT), with the 3D Map consistently showing longer time to first fixation and longer dwell times. These findings indicate lower cognitive efficiency and greater visual processing effort compared to the 2D map variants. Therefore, hypothesis 1, which assumed that a web service with a static 3D map would demonstrate higher usability (simplicity, intuitiveness, and efficiency) than a service with an interactive 2D map, is not supported by the objective behavioural data. In terms of efficiency and intuitiveness, the 2D maps, particularly the simplified Leaflet-based versions, proved more effective.

However, the survey results revealed a different pattern. Despite weaker objective performance, the 3D Map received the highest overall usability and satisfaction scores and differed significantly from both Street View Maps and Leaflet Maps (Kruskal-Wallis test, $p < 0.001$, very large effect size). Participants rated the 3D interface as more visually appealing, engaging, and easier to remember. These findings support hypothesis 2, suggesting that a static 3D map, even without advanced interaction

mechanisms, may generate higher subjective user satisfaction than interactive 2D solutions.

Overall, the study highlights a clear discrepancy between objective usability indicators and subjective user preferences. While 2D interactive maps enable more efficient task performance and reduced cognitive load, 3D visualization enhances perceived attractiveness and satisfaction. These findings underline the importance of balancing functional efficiency with experiential and aesthetic qualities when designing web services that incorporate interactive maps.

A limitation of this study is the small sample size and its homogeneity, resulting from the fact that all participants were students from the same faculty at the same university. These circumstances may limit the generalizability of the obtained results. Future studies should include larger samples and consider participants with greater diversity in terms of age, educational background, and digital competencies.

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