WEB-BASED 3D HEATMAP VISUALIZATION OF SPATIAL COGNITION USING EEG AND EYE TRACKING DATA

TAE HO CHOI[1], SEUNG YEUL JI[2], YI YEON HONG[3]and HAN JONG JUN[4]

[1,2,3,4] Hanyang University, Korea.
[1]xogh0gye3@hanyang.ac.kr, 0009-0002-5665-5607
[2]musicji83@hanyang.ac.kr, 0000-0003-1268-0384
[3]su08069@hanyang.ac.kr, 0009-0007-7007-141X
[4]hanjong@hanyang.ac.kr, 0000-0003-1798-183X

Abstract. In recent years, the field of architecture has emphasized a user-centered approach. The focus is on analyzing and visualizing users' cognitive and emotional responses to the architectural environment to understand how it affects their experience beyond physical space. This study integrates eye-tracking technology and electroencephalography to analyze the user's visual attention and emotional state and perform web-based visualization. Eye tracking records a user's eye movements to identify areas of visual interest and concentration, while Electroencephalography measures alpha and beta wave activity to evaluate concentration and nervousness. The interrelationship between eye tracking and Electroencephalography data is identified using a time-series-based synchronized dataset. To visualize the analyzed biometric data in 3D, we map the data against the background of PointCloud as a 3D environment using Cesium, which is based on WebGL. The use of 3D visualization allows for the demonstration of the interaction between the user's biological response and architectural elements in a three-dimensional format. This enables a more intuitive understanding of users' cognitive and emotional responses within the architectural environment.

Keywords. User perception method, Smart Space, Visualization, Eye-Tracking, EEG, WebGL, Cesium.

1. Introduction

Recently, the field of architecture has been shifting towards a more user-centered approach. The built environment extends beyond mere physical space design; it impacts the lives of individuals by shaping their interactions and experiences within it (Annemans, et al 2014). Architectural planning facilitates diverse user experiences through user interaction with architectural elements An approach that focuses on the needs and preferences of users can significantly improve people's lives, thereby giving

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 3, 529-538. © 2024 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

architecture intrinsic value and meaning(Tvedebrink and Jelić, 2018).

To achieve this, it is important to understand how users perceive and interact with the built environment. Advances in biometric data measurement technologies are making it possible to quantitatively analyze user reactions in the built environment based on biometric data. This will provide insights for analyzing and utilizing cognition and activity in the built environment (Mostafavi, 2021). Therefore, in order to understand the cognitive style of users, data using eye tracking and electroencephalography (EEG) will be collected and analyzed to identify user reactions and areas of interest.

To interpret the analyzed data, three-dimensional visualization of biometric data is necessary. This is a method to understand the user's biological response in a three-dimensional architectural space, and can reveal the connection between architectural elements and the user's response. In this way, biometric data visualization using 3D visualization techniques will be able to intuitively understand the causal influence of architectural space and architectural elements on cognitive and emotional responses during the user experience.

Web-based visualization methods are well suited to effectively represent various biometric information in a three-dimensional environment. Advances in web-based three-dimensional graphical rendering technology have made it possible to recreate the built environment, making it more accessible and navigable (Krooks, et al 2014). Web-based platforms can provide user interfaces that allow users to utilize data from multiple perspectives.

In this study, we aim to visually represent cognitive processes and emotional information in the built environment by analyzing synchronized eye-tracking and EEG data in a web-based three-dimensional environment. To achieve this goal, it is important to identify the elements to be visualized according to the interpretation method. Through experiments, eye tracking and EEG data were collected and analyzed to identify correlations and visualized in three dimensions using web-based graphics. This will enable the integration of biometric data and three-dimensional visualization to provide insights into user experience and reactions in built environments.

2. Theoretical Discussions

2.1. EYE TRACKING ANALYSIS METHOD.

We investigate whether eye-tracking technology can reveal users' visual preferences and areas of interest. Eye-tracking records the user's eye movements using a camera to collect critical data about visual attention and cognitive processes(Cho, et al 2022). Important indicators of eye tracking include Areas of Interest (AOI), Gaze Plot, Fixation, and Time of Gaze. As shown in Table 1, gaze metrics can be used to understand how long a user focuses on a particular visual stimulus and how their gaze moves in space, which translates into the user's visual preference and concentration.

Table 1. Eye Tracking Analysis Methods for Assessing Visual Responses

Analysis Method	Content	Interpretation Method
Heat Map	Overall patterns of gaze concentration and distribution	Visual Concentration Area Representation
Gaze Plot	Tracking the movement path of gaze	Gaze Movement Pattern Analysis
Binning Chart	Analysis of Area of Interest (AOI) data over a specified time	Area of Interest Concentration Assessment

2.2. BRAIN WAVE ANALYSIS METHOD

Brain waves are categorized by frequency, with alpha waves (8-14 Hz) appearing in relaxed and focused environments, making them a useful measure of concentration in those environments. Beta waves(14-30Hz), on the other hand, are associated with stress, including tension and alertness. They can appear when a user is in a complex or stimulating environment and are an important indicator for understanding stress levels and tension in a space (Abhang, et al 2016). Therefore, analysis using EEG can help us understand how elements or areas of the built environment affect our cognitive and emotional responses, as shown in Table 2.

Table 2. EEG Data Analysis Methods for Understanding Responses

Analysis Method	Content	Interpretation Method
Brainwave Visualization	Visualizing brainwave activities in different brain regions	Cognitive and Emotional State Interpretation
Time-Series Brainwave Analysis	Changes in brainwave patterns over time	Dynamic Cognitive and Emotional Response Assessment

Eye tracking and EEG data interpretation can be used to understand gaze and emotional information, so combining the two biometric data can accurately identify the impact of the built environment on users' cognitive processes and emotions (Nakanishi and Hattori, 2017).

2.3. 3D VISUALIZATION METHOD

We aim to reproduce a sense of space through relative position by visually expressing this biometric information and expressing it in a 3D environment so that the correlation with architectural elements can be easily understood. As a way to do this, when observing a three-dimensional space, the focus moves according to the depth of gaze. In order to express gaze data in a three-dimensional way from a two-dimensional image captured by a camera, gaze depth information is required (Thies and Cem, 2016). To generate depth information from 2D, a 3D reference object is essential. Using the perspective-n-point technique, the user's position and orientation are estimated, vector values are extracted from points in the 2D object according to the gaze direction, and depth information is inferred by finding the intersection with the 3D object (Stein, et al. 2023). To achieve this, we use lidar scanning technology to visualize biometric data against the background of a 3D point cloud as a 3D reference object.

Among various web-based visualization tools, we plan to use Cesium, a WebGL library with excellent geospatial visualization and real-time rendering using 3DTile. Cesium accurately visualizes location information using a GPS-based coordinate system, allowing users to know the relative location of buildings and GPS coordinates, and is mainly used in GIS visualization research (Hillmann, et al. 2022). Cesium has been used to accurately visualize data using the PointCloud visualization method and point-based coordinate data.

3. Eye tracking and brainwave experiment process

3.1. EXPERIMENT ENVIRONMENT

To collect cognitive responses to architectural elements, we experimented with the ‘DonorWall’ object located in the lobby, as shown in Figure 1. Gaze movements and brain waves were recorded using Tobii Glasses 2 and Open BCI's 8-channel board tool(Alarcão and Fonseca, 2019), and resulting data were collected. The Donor Wall is a visual stimulus consisting of mosaics of varying sizes and colors representing the amount of money donated toward the construction of the Experimental Building. We aim to investigate whether random placement of objects can affect attention, memory, and emotional responses.

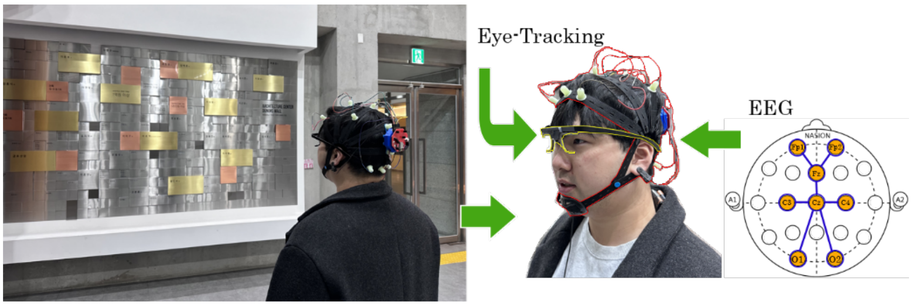

Figure.1 Experimental equipment and test sense

3.2. EYE TRACKING AND EEG DATA SYNCHRONIZATION

In order to correlate the eye tracking and EEG data, we need to determine the sampling rate of each data. The eye tracking data is collected at 50 Hz and the EEG data is collected at 250 Hz. To reconcile these differences, we unified the different types of timestamps into real-time timestamps and matched the start points of data collection, then averaged the 250 Hz EEG data and downsampled it to 50 Hz. This created a temporally synchronized dataset and allowed for time-series-based data analysis.

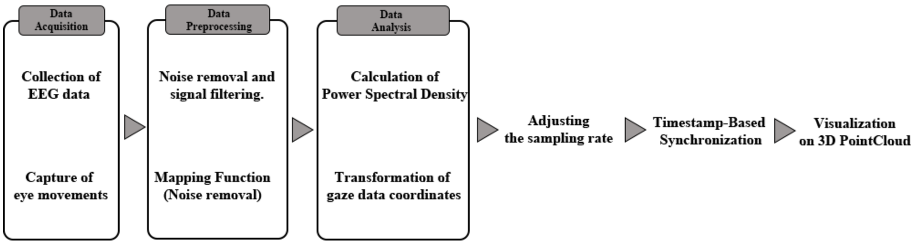

Figure 2. Synchronizing EEG with eye tracking

3.3. EYE TRACKING ANALYSIS

To analyze the eye-tracking data, we established areas of interest (AOI) for different amounts: 100 million won (yellow), 50 million won (orange), 20 million won (red), 10 million won (green), 5 million won (blue), and Title (sky). These areas were set according to the depicted amounts in Figure 3, and we then proceeded to analyze the distribution of gazes. The interpretation of gaze preference and concentration is based on the quantity of observer gazes and the amount of time devoted to each object. Upon analysis of Table 3's gaze data for areas of interest, it can be observed that Fixation count and gaze duration are relatively high in the case of 100 Million and 50 Million, where size and color are prominent. However, for 5 Million, the low fixation but long attention span is due to the part where many names are written in a small area, and it is interpreted that concentration appears. The analyzed data can be portrayed visually through a heatmap, as illustrated in Figure 4.

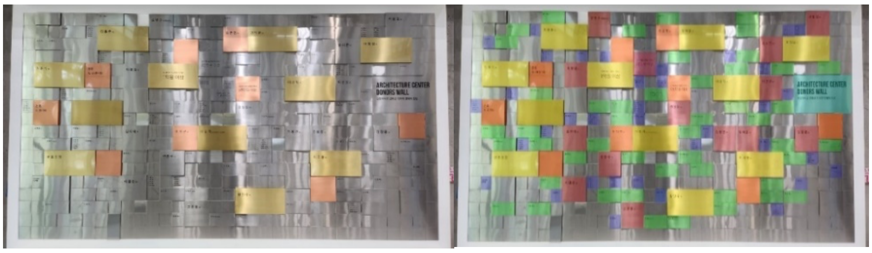

Figure 3. Donor Wall Experimental Area and AOI(Areas Of Interest)

Table 3. Time and Number of gazes on AOI

AOI	Count	Longest time(s)	Average time(s)
100 Million	56	2.02	0.39
50 Million	26	3.12	0.65
20 Million	24	3.00	0.43
10 Million	48	2.30	0.40
5 Million	9	4.04	0.54
Title	1	0.88	0.88

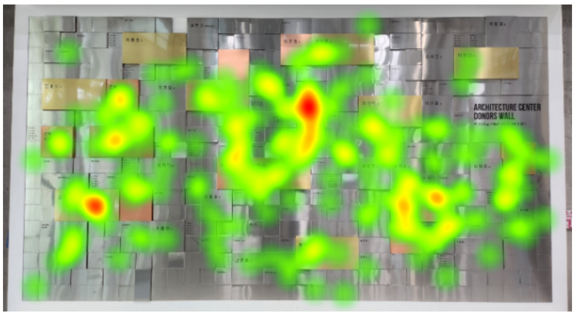

Figure 4. Heatmap of Gaze Concentration

3.4. ANALYZE EEG DATA

The MNE methodology calculates the power spectral density (PSD) of a specific frequency band from EEG data (Gramfort A et al., 2013). A bandpass filter is applied to the time series data of each EEG channel to extract the desired frequency band, and the power values of the alpha and beta waves are obtained by calculating the amplitude of the signal using the Hilbert transform. In order to relate it to the point of view, we mapped the EEG data to the gaze coordinates according to the time series information.

3.4.1. Alpha wave data analysis

As shown in Figure 5, alpha wave mapping reveals a high concentration around certain areas of interest on the donor wall. These areas are typically high donation parts of the donor list, which translates into increased alpha wave activity as users view the size of the donation as an impressive factor.

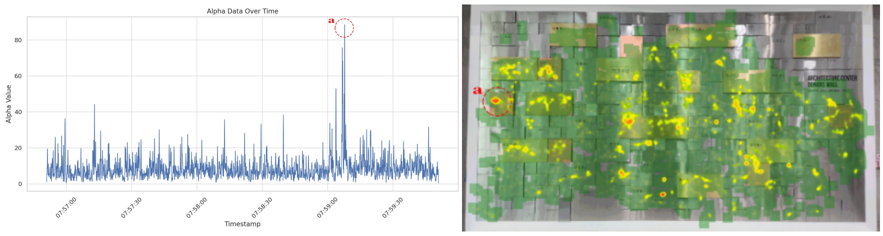

Figure 5. Alpha Wave Responses Over Time and Heatmap on Gaze point

3.4.2. *Beta wave data analysis*

On the other hand, in Figure 6, beta waves, which represent tension and stress levels, are not limited to specific areas of interest on the Do-nor wall, but are distributed throughout. This is interpreted as an increase in beta wave activity when the user is looking at a visually complex element.

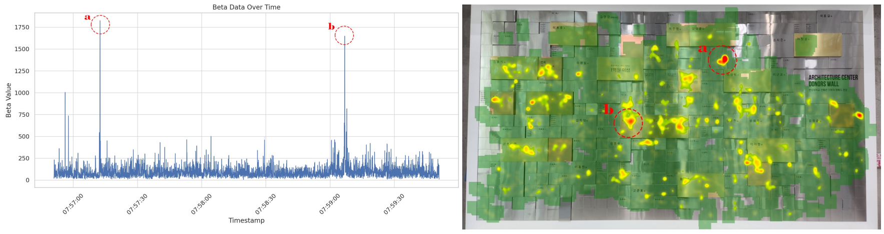

Figure 6. Beta Wave Responses Over Time and Heatmap on Gaze point

Through analysis of alpha and beta waves and distribution maps, it is possible to understand the emotional information conveyed by the visual stimulation provided by Donor Wall to users. This understanding can provide important insights into the design of architectural elements and the user experience, by revealing how specific visual stimuli trigger different emotional responses.

4. 3D Coordinates of Gaze

To visualize EEG data analyzed by gaze position in three dimensions, we want to obtain three-dimensional coordinates from two-dimensional gaze data. First, we identify the user's position by perspective n points, as shown in Figure 7. To match the three-dimensional pointcloud and the analyzed data with the mapped image, we extract the camera (user's position) location information by matching four points with the target sticker used in the lidar scan process, as shown in Figure 8. In addition, using this in reverse, a vector value is created by the user's position and the coordinates of the gaze point in the image, and the three-dimensional coordinates are inferred through the intersection point with a three-dimensional object (Liu, et al. 2020). This allows the flow of gaze to be expressed by organizing coordinate points based on time series, and it will be helpful for data interpretation by expressing a sense of space through relative positions.

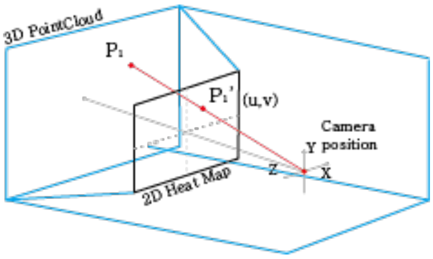

Figure 7. Perspective-n-point

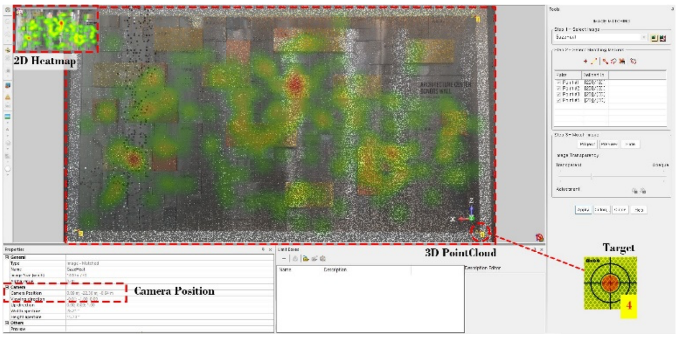

Figure 8. Camera position and Heatmap mapping

5. Web-based visualization

As a way to save rendering resources and easily render three-dimensional objects for web-based visualization, Point-Clouds can be converted to 3DTiles using a library called Cesium. However, making direct changes to the converted object can be challenging. Therefore, we mapped the heatmap with biometric data directly to the PointCloud based on gaze coordinates and displayed the converted and mapped PointCloud. Additionally, by utilizing Cecium's Clock feature, we can observe changes over time. Thus, we expressed the flow of gaze by overlaying gaze points on objects, according to time series information. Users can easily understand the distribution of gaze and emotional information by analyzing the mapped data and comparing it to the flow of gaze. Additionally, we provide supplementary information through an additional UI to help users comprehend their cognitive factors.

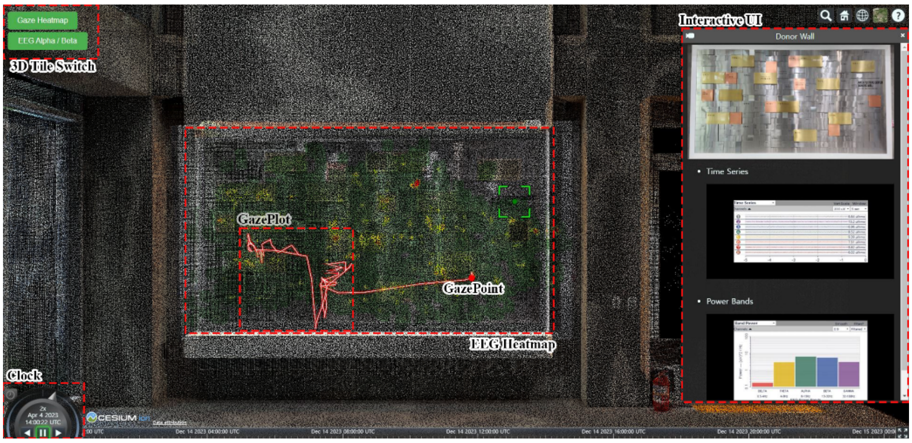

Figure 9. Web 3D PointCloud Visualization

6. Conclusion and Future Research

This study examines the cognitive and emotional responses of users in architectural environments and proposes effective visualization methods. The study analyzes eye-tracking and brainwave data to identify how specific architectural elements affect the user experience. By visually comparing these correlations, the interaction between architectural elements and user responses can be evaluated and understood. Three-dimensional expression through 3D visualization can be a crucial indicator to more accurately analyze users' cognitive and emotional responses to the architectural environment, and thus find ways to optimize the user experience.

In future research, we plan to expand the subject from architectural elements to specific spaces and develop visualization methods that focus on temporal changes and spatial movements. As this is a PointCloud visualization, it can accurately convey the sense of space and coordinates based on relative depth values through point coordinate calculation. These methods of expression can provide a deeper understanding of user experience and cognitive responses in the architectural environment.

Acknowledgements

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2022R1A2C3011796).

Reference

Annemans, Margo., Audenhove, Chantal., Vermolen, Hilde & Heylighen, Ann. (2014). How to Introduce Experiential User Data: The Use of Information in Architects’ Design Process.

Tvedebrink, T., & Jelić, A. (2018). Getting under the(ir) skin: Applying personas and scenarios with body-environment research for improved understanding of users' perspective in architectural design. Persona Studies. https://doi.org/10.21153/PSJ2018VOL4NO2ART746.

Mostafavi, A. (2021). Architecture, biometrics, and virtual environments triangulation: a research review. Architectural Science Review, 65, 504 - 521. https://doi.org/10.1080/00038628.2021.2008300.

Krooks, A., Kähkönen, J., Lehto, L., Latvala, P., Karjalainen, M., & Honkavaara, E. (2014). WebGL Visualisation of 3D Environmental Models Based on Finnish Open Geospatial Data Sets. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 163-169. https://doi.org/10.5194/ISPRSARCHIVES-XL-3-163-2014.

Cho, Ji Young., Kim, Ju Yeon., & Kim, Jong Ha (2022). Visual Cognitive Style and Size Perception in a Virtual Environment. Design convergence study. vol. 21, no. 5. 17-30.

Nakanishi, I., & Hattori, M. (2017). Biometric potential of brain waves evoked by invisible visual stimulation. 2017 International Conference on Biometrics and Kansei Engineering (ICBAKE), 94-99. https://doi.org/10.1109/ICBAKE.2017.8090644.

Abhang, P. A., Gawali, B. W., & Mehrotra, S. C. (2016). Introduction to EEG-and speech-based emotion recognition. Academic Press.

Gramfort A., Luessi M., Larson E., Engemann DA., Strohmeier D., Brodbeck C., Goj R., Jas M., Brooks T., Parkkonen L., & Hämäläinen M (2013) MEG and EEG data analysis with MNE-Python. Front. Neurosci. 7:267. doi: 10.3389/fnins.2013.00267

Alarcão, S.M., & Fonseca, M.J. (2019). Emotions Recognition Using EEG Signals: A Survey. IEEE Transactions on Affective Computing, 10, 374-393.

Thies Pfeiffer., & Cem Memili. (2016). Model-based real-time visualization of realistic three-dimensional heat maps for mobile eye tracking and eye tracking in virtual reality. In Proceedings of the Ninth Biennial ACM Symposium on Eye Tracking Research & Applications (ETRA '16). Association for Computing Machinery, New York, NY, USA, 95–102. https://doi.org/10.1145/2857491.2857541

Stein, Isabell., Jossberger, Helen., & Gruber, Hans. (2023). MAP3D: An explorative approach for automatic mapping of real-world eye-tracking data on a virtual 3D model. Journal of Eye Movement Research. 15. 10.16910/jemr.15.3.8.

Hillmann, Malte., Felix Igelbrink., & Thomas Wiemann. (2022). COMPUTING ARBITRARILY LARGE MESHES WITH LEVEL-OF-DETAIL SUPPORT FOR CESIUM 3D TILES. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 48, 109-116.

Liu, M., Li, Y., & Liu, H. (2020). 3D Gaze Estimation for Head-Mounted Eye Tracking System With Auto-Calibration Method. IEEE Access, 8, 104207-104215. https://doi.org/10.1109/ACCESS.2020.2999633.