REAL-TIME USER EXPERIENCE AND EMOTIONAL STATE TRACKING IN INDOOR ARCHITECTURAL SPACES USING CHATGPT API AND EEG

SEUNG YEUL JI [1], MI KYOUNG KIM[2] and HAN JONG JUN[3]

[1,2,3] Hanyang University, Korea.
[1]musicji83@hanyang.ac.kr, 0000-0003-1268-0384
[2]nnyang2mk@hanyang.ac.kr, 0000-0002-6692-405X
[3]hanjong@hanyang.ac.kr, 0000-0003-1798-183X

Abstract. Technological advances have revolutionized our perception of human interactions in architectural spaces. In this study, EEG for brainwave analysis, LiDAR for spatial scanning, and ESP32 UWB for position detection were integrated into Unity3D and analyzed using the ChatGPT API. Our goal was to enhance the human experience by visualizing real-time positions, emotions, and reactions in architectural environments. The project started with 3D scanning to create a digital twin model in Unity3D, which was transformed into a virtual space with a 5x5 grid to capture EEG data. The data was analyzed using the Wolfram Mathematica API and a ranking algorithm, complemented by the ChatGPT API, fine-tuned with the SEED dataset for comprehensive emotion recognition. The core feature of the system was heat maps for visualizing emotional responses, using Unity3D's dynamic particle system for a more immersive and three-dimensional representation. This advanced approach provides architects and designers with deeper insight into user-centered space design. In summary, our integrated system demonstrates significant potential for understanding and enhancing the user experience in architectural spaces by providing insight into the impact of design elements on emotional states. It's a step forward in intelligent building and urban design that focuses on human well-being and satisfaction.

Keywords. EEG, ChatGPT API, Wolfram Mathematica API, LiDAR Scanners, ESP32 UWB, Unity3D

1. Introduction

As modern people spend more and more time indoors, this study highlights the importance of indoor design and its impact on individual health, productivity, and quality of life. In particular, it points to the need to deeply understand users' behaviors, emotions, and perceptions in indoor environments, and proposes a new methodology that combines and reconfigures the latest edge technologies to do so.

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 3, 479-488. © 2024 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

It points out that traditional methods of user experience analysis, such as surveys, interviews, and observations, are subjective and limited, and that a data-driven approach is needed. The approach proposed in this study uses innovative technologies such as LiDAR scanning, ultra-wideband modules, and EEG data acquisition systems to collect information about users' interactions with the environment in real time.

The goal of this research is to build an integrated data-driven system that can comprehensively analyze the user's location, experience, and reactions in an indoor architectural space. To achieve this, several technologies will be used in an integrated manner, in particular EEG data will be collected using the Enobio EEG 32 device. The device is the Enobio EEG 32, which is CE marked as a Class IIa medical device under the Council Directive 93/42/EEC on medical devices (EC certificate ES19/86968) and licensed as a Class 2 medical device under the Canadian Medical Device Regulations, SOR 98/282 (license number: 90344).

The system implemented in this research monitors the user's location and responses in a unique way. The system tracks the user's emotions and behaviors in real time and represents this data visually in space, specifically in the form of a heat map. The heatmap visualization method borrows and applies visual effects (VFX) techniques from the gaming industry. As a result, it provides an intuitive and dynamic way to understand how the distribution of users' activities and emotions affects the space, and can contribute to improving the quality of life in smart buildings and urban planning, although limited to the field of architecture.

1.1. RESEARCH METHODS.

This research addresses an integrated data-driven system designed to comprehensively understand how users move, feel, and react in indoor architectural spaces. The methodology for developing this system is as follows:

- 3D scanning and virtual environment recreation: This study collects three-dimensional point data of an indoor space and recreates it as a virtual environment using the Unity3D game engine.
- Develop a user location tracking system: Develop a system that accurately tracks a user's movements indoors using ESP32 UWB technology.
- Collect brainwave data and analyze emotions: Collect users' brainwave data in real-time using an Enobio EEG 32-channel device, and analyze it to understand their emotional responses.
- Visualize emotional responses: Use heatmaps to effectively interpret and communicate user emotional responses.
- Use comprehensive data analysis tools: Build a tuning model based on the ChatGPT API and combine it with the Wolfram Mathematica API to perform comprehensive data analysis on the effectiveness of user experience and design elements.

2. Theoretical Discussions

2.1. USER EXPERIENCE AND INTERIOR SPACES.

Exploring user experience in indoor environments is vital in architecture, interior design, and environmental psychology. It's essential to understand user perception and interaction to enhance health, productivity, and satisfaction. Key elements, including space layout, color, lighting, and furniture, significantly influence users' emotions and behaviors. For instance, optimal lighting and color schemes have been found to reduce stress and boost satisfaction, thus benefiting health.

Technological advancements, particularly in VR and AR, have transformed research methods, allowing deeper, controlled exploration of user experiences. However, a gap exists in capturing and analyzing real-time user positional awareness, emotions, and reactions. Integrating LiDAR scanners, Unity3D, ESP32 UWB, and EEG systems, this research aims to develop a comprehensive system for insightful interior space design analysis.

2.2. ARCHITECTURAL SPATIAL RECOGNITION AND LIDAR

LiDAR technology has revolutionized three-dimensional modeling of architectural spaces. By using laser pulses to measure distance, the technology provides detailed geometric characteristics of indoor and outdoor environments as high-resolution point clouds. It is playing an important role in a variety of fields, including building documentation, historic preservation, and remodeling projects. LiDAR scanners are also being used to analyze user experience in indoor spaces. The accurate 3D models they create, combined with virtual reality (VR) or game engine platforms like Unity3D, enable research into user behavior, emotions, and perceptions. This approach enables data-driven analysis without altering the physical space. In this study, we use LiDAR scanners to collect detailed 3D data of indoor architectural spaces and integrate them into the Unity3D game engine to provide an immersive spatial representation for real-time analysis of users' locations, emotions, and reactions.

2.3. LOCATION AWARENESS USING ULTRA-WIDEBAND (UWB)

UWB technology plays a key role in providing accurate location awareness data in real time. This wireless communication technology has a wide frequency range and low power consumption to provide precise ranging and location information in complex environments. This is very useful in indoor environments where other technologies such as GPS, Wi-Fi, and Bluetooth are not effective. UWB-based systems have been widely applied in indoor positioning and navigation applications. These systems use UWB anchors and tags to track a user's location in real time, and the collected data is processed on a server. In this study, we develop a user localization system in indoor architectural spaces using the ESP32 UWB module. The system accurately tracks the user's movements, providing data on their behavior and experience in the indoor environment. By integrating UWB technology with the Unity3D game engine and EEG data acquisition system, a comprehensive real-time analysis of user location, emotions, and reactions becomes possible. This allows you to observe the user's actual movements as they are reflected in the virtual world in real time. As a way to implement such a system based on the game engine, we developed a code based on the Unity Projects by That Project to connect with EEG (Figure 1).

2.4. SENTIMENT ANALYSIS RESEARCH USING EEG DATA

EEG data analysis is pivotal in understanding human emotions and cognition. This study uses the Shanghai Jiaotong University Emotion EEG Dataset (SEED), which records EEG data from participants watching emotive videos. The SEED dataset, with its 62 channels and 200 Hz sampling frequency, has proven effective in emotion recognition research.

We applied change point detection to analyze EEG data for emotion classification. This technique identifies significant shifts in time series data, allowing real-time

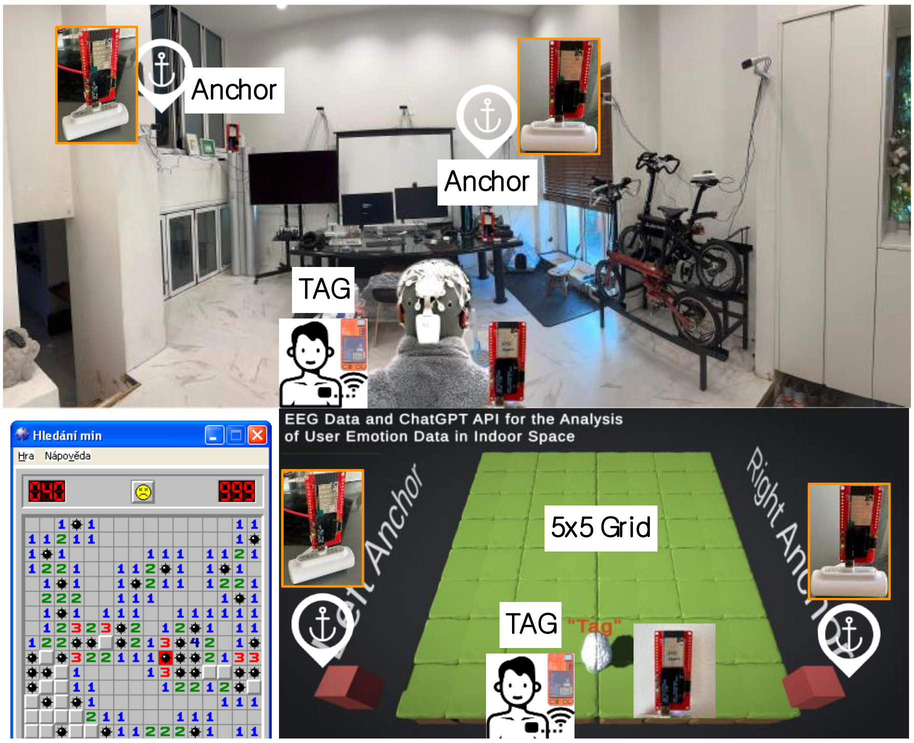

Figure 1 Convergence of real and virtual: Implementation of location system using UWB

analysis of emotional states. Using the Enobio EEG 32-channel device, we tracked and evaluated emotional responses in an indoor setting. The data, integrated with a UWB-based location system and Unity3D engine, enhances our understanding of human emotions in architectural spaces.

A summary table of the study's key components is as follows:

TABLE 1. Components and Tools for EEG Data Analysis and Emotional Response Evaluation in Indoor Spaces

Component	Description	Dataset/Tool	Application Area

SEED Dataset	EEG dataset provided by Shanghai Jiaotong University's BMIS, containing brainwave data recorded while participants watched emotionally evocative videos.	Shanghai Jiaotong University Emotion EEG Dataset	Emotion recognition, Brain-computer interfaces, Brain signal processing
OpenAI Fine-tuning	Process of adjusting a pre-trained model to suit the characteristics of the SEED dataset.	OpenAI	Machine learning, Emotion classification, Data interpretation
Wolfram Mathematica	Powerful tool for data import, manipulation, and visualization, used for data analysis and processing.	Wolfram Mathematica	Data analysis, Statistical processing, Visualization
EEG Measurement Device (Enobio)	Device used for tracking and evaluating users' emotional responses in real-time in indoor spaces.	Enobio EEG 32-Channel Device	Neuroscience, Real-time data collection, Emotion analysis

3. Build a user sentiment data analysis system

3.1. COLLECT AND PROCESS INDOOR SPACE

3.1.1. Real-world spatial data analysis methodology

This research employs LiDAR technology for collecting high-resolution 3D point data, crucial for analyzing interior architectural spaces. LiDAR, short for Light Detection and Ranging, uses laser light to measure distances, creating detailed 3D representations of environments. LiDAR scanners, positioned at specific locations, emit laser pulses and measure their return time to form dense point clouds of indoor spaces. These clouds undergo alignment and registration, using common reference points or algorithms, to create a unified 3D model. The accuracy of this model is meticulously checked to ensure comprehensive representation of all relevant areas.

The processed data is then formatted for compatibility with the Unity3D game engine, facilitating a virtual environment for real-time analysis of user experience. This approach provides valuable insights into user behavior and reactions in interior spaces, enhancing our understanding of architectural design and user interaction(Figure 2).

Figure 2 Indoor space scanning with Trimble SX12

3.2. HOW TO ANALYZE VIRTUAL WORLD SPATIAL DATA

In this study, we transformed LiDAR point cloud data of an indoor space into a virtual environment using Unity3D, a powerful platform for creating 3D interactions. The process involves several key steps:

- Data Conversion: LiDAR data is converted to a Unity3D-compatible format (like OBJ or FBX) using tools like Point Cloud Viewer and Tools.
- 3D Model Import: The converted data is then imported into Unity3D, scaled and positioned accurately within the virtual environment.
- User Location Tracking: An ESP32 UWB-based system is integrated for real-time user location tracking in the indoor space.
- Data Visualization: Tools like heatmaps and graphics are developed to visualize user emotional responses and eye positions.

3.3. HOW TO COLLECT AND ANALYZE REAL-TIME EEG DATA

This research focuses on real-time brainwave data collection and analysis to enhance user experience in architectural spaces. Such data informs us about users' emotional and cognitive states, crucial for architects and designers in understanding the impact of interior design on user experience.

Key steps in this process include:

- EEG Data Collection: Using devices like the Enobio EEG 32-channel system, we collect real-time EEG data from users.
- LSL Protocol Utilization: The Lab Streaming Layer (LSL) protocol synchronizes data streams from various devices, essential for concurrent processing of user location data (from ESP32 UWB systems) and EEG data. This synchronization is vital for correlating user emotions with their locations (Figure 3)

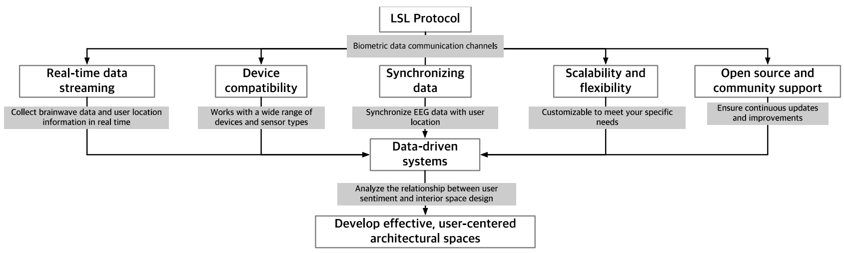

Figure 3 The role of the LSL protocol in EEG data and user location information in real-time

3.4. BUILDING A FINE-TUNING MODEL WITH CHATGPT API AND COMPREHENSIVE DATA ANALYSIS

To analyze user experience in architectural spaces, we perform a comprehensive sentiment analysis with a fine-tuning model that combines EEG data and ChatGPT API. The training set for the fine-tuning model is based on the SEED dataset,and the

ChatGPT model is fine-tuned to effectively classify emotional states. We use embedding technology to convert EEG data into vector form and train the model based on emotion labels. We select and use EEG channels (Fp1, Fp2, Fz, C3, Cz, C4, O1, O2) from the frontal and temporal lobes. As of Q3 2023, the hyper-parameter of API fine-tuning based on ChatGPT cannot be adjusted by limiting the number of epochs, the epoch value is limited to 3, and the AI model is trained with the same EEG data set 3 times. The module for a prompt for fine-tuning was composed of 163 tokens as a training set, and a total of 507,441 tokens were used for fine-tuning(Figure 4).

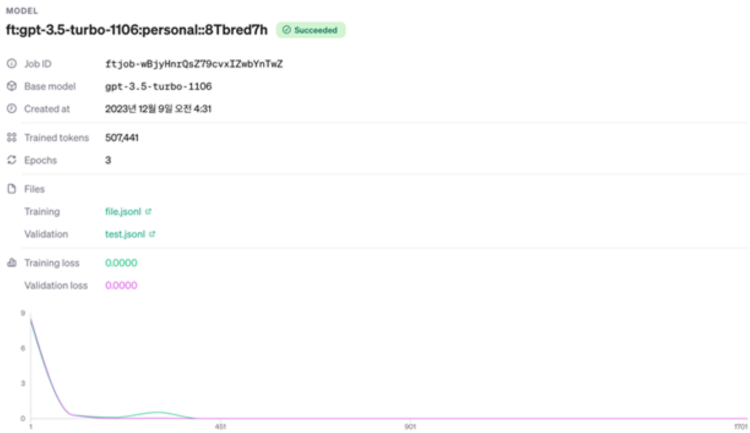

Figure 4 Fine Tuning Model Training Results

As a result of model training, the fine-tuned ChatGPT model effectively classifies emotional states in architectural spaces based on EEG data and serves as a data output for prediction and visualization.In conclusion, the integration of the ChatGPT API into this data-driven system provides comprehensive analysis and insight into the perception and user experience of indoor spaces, leading to effective user-centered architectural design.

As the person wearing the UWB moves through the room, each grid block can record EEG-based emotional information, similar to a game of Minesweeper, and the accumulated data is distributed to each grid using a numerical ranking operation in the Wolfram API (Figure 5).

4. Visualization of Heatmaps: 2D and 3D Brainwave Data-Based Heatmap

4.1. CREATING A HEATMAP

In this research, we utilized the Wolfram Mathematica and ChatGPT APIs to analyze EEG data collected from users navigating a 5x5 block grid in a Unity3D virtual environment, representing physical space through ESP UWB technology. The data analysis focused on the average alpha and beta wave values from each block. This information was then used to generate heatmaps, with color darkness indicating the intensity of emotional responses. These heatmaps provide valuable insights into user emotional states, aiding in the development of user-centered architectural design strategies.This system effectively integrates advanced analytics and EEG data to enhance understanding of user experiences in architectural spaces. In the heatmap in Figure 6, higher values of alpha waves are colored red and higher values of beta waves are colored blue, so darker red areas indicate locations where the user had a positive response and darker blue areas indicate locations where the user had a negative response. We can integrate this heatmap into the Unity3D environment to visualize the spatial experience based on the user's EEG response. We will calculate the average value of alpha and beta waves in each block and then calculate a ranking based on the average value using a formula to determine the positivity or negativity of the block. Alpha waves are defined as positive brain waves, and beta waves are defined as negative brain waves, such as stress. Therefore, blocks with higher alpha wave readings, indicating a positive response, and lower beta wave readings, indicating a negative response, will have a higher ranking.

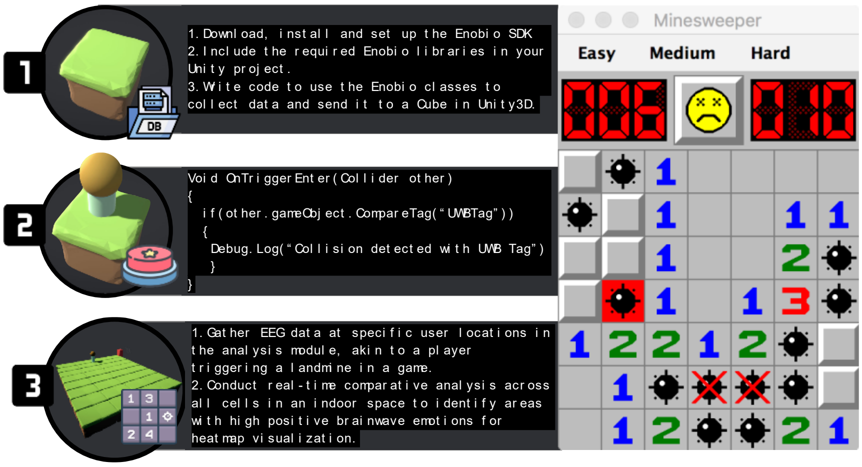

Figure 6 Emotional information visualization mechanism using EEG and UWB

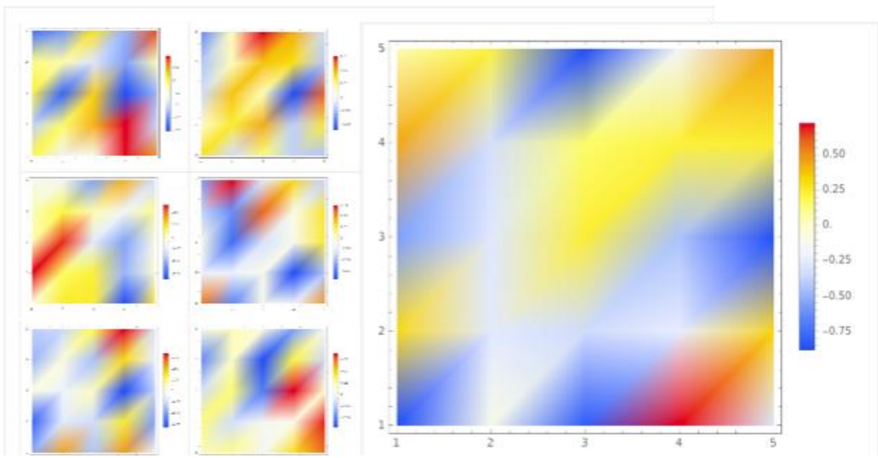

Figure 5 Comparative Heatmap Analysis of Alpha and Beta Brainwave in User Experience

4.2. HEATMAP VISUALIZATION AND VFX WITH UNITY3D

This study covers visualizing information from two-dimensional heatmaps based on the Wolfram Mathematica API and ChatGPT API using Unity3D's Visual Effect Graph (VFX). The focus is on making the representation of users' emotional data more intuitive and dynamic. The VFX Graph in Unity3D is a powerful tool that allows you to create complex particle systems with a high degree of control and flexibility. It provides a visual representation of the intensity of an emotion based on the average value of collected EEG data. The color of each block depends on the alpha and beta wave values and represents the intensity of the emotion(Figure 7).

- VFX implementation: Using Unity3D's VFX Graph, dynamically visualize a heatmap based on each block's EEG data. This visualization reflects emotional changes in real time as the user experiences each block.
- Particle system: Leverage Unity3D's powerful particle system to represent emotional data as a flow of particles or a change in color. This gives you a more detailed representation of how a user's emotional changes are represented in space.
- Diversity of emotional expression: Use different colors and dynamic particle effects to represent different aspects of an emotion. For example, positive emotions can be visualized with bright, warm colors, and negative emotions with darker colors.

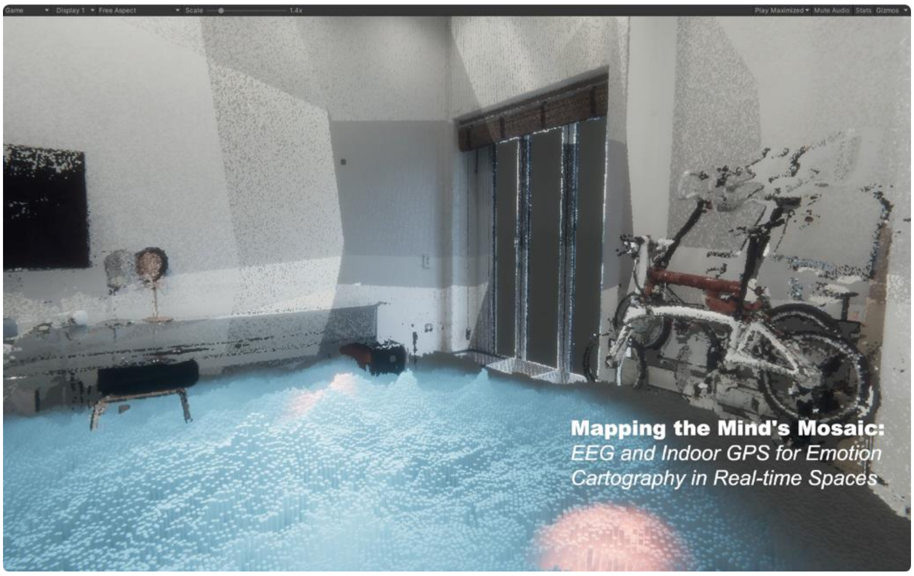

Figure 7 Three-dimensional visualization of emotional expression using brainwaves

5. Conclusion and Future Research

This study developed a data-driven system integrating LiDAR, Unity3D, ESP32 UWB, and EEG technologies to analyze user experience in indoor spaces. Key achievements include recreating 3D indoor environments, accurately tracking user location and movements, and real-time analysis of brainwave data for emotional insights. Heatmap visualizations and the ChatGPT API provided a deeper understanding of the impact of space design on user emotions. These insights empower architects and designers to make educated, user-centered design decisions, optimizing space utilization and adaptability. Future research will focus on expanding these methodologies to a wider range of architectural and urban planning contexts, further integrating data-driven approaches in designing spaces that enhance user experience and well-being.

Acknowledgements

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

Reference

Alalouch, C., Aspinall, P., & Smith, H. (2016). Using virtual reality to investigate user experience in indoor spaces. In Proceedings of the 3rd International Conference on VR Technologies in Cultural Heritage (pp. 1-8).

Getting Started with ESP32 DW1000 UWB (Ultra Wideband) Module. How To Electronics. https://how2electronics.com/getting-started-with-esp32-dw1000-uwb-ultra-wideband-module/ 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.

M. Aljehani et al., "A 3D point cloud-based indoor mapping system using a 2D laser scanner," IEEE Access, vol. 8, pp. 15367-15379, 2020.

Y. Li et al., "An ESP32 UWB-based indoor localization system," IEEE Internet of Things

Gannouni, S., Aledaily, A., Belwafi, K., et al., 2021. Emotion detection using electroencephalography signals and a zero-time windowing-based epoch estimation and relevant electrode identification. Sci Rep, 11, 7071. https://doi.org/10.1038/s41598-021-86345-5

Galvez-Pol, A., Nadal, M., Kilner, J.M., 2021. Emotional representations of space vary as a function of peoples' affect and interoceptive sensibility. Sci Rep, 11, 16150. https://doi.org/10.1038/s41598-021-95081-9

Vischer J.C. (2008) Towards an Environmental Psychology of Workspace: How People are Affected by Environments for Work. Architectural Science Review 51(2):97-108. DOI: 10.3763/asre.2008.5114

Küller R., Ballal S., Laike T., Mikellides B., Tonello G. (2006) The impact of light and colour on psychological mood: a cross-cultural study of indoor work environments. Ergonomics 49(14):1496-1507. DOI: 10.1080/00140130600858142

Riva G., Mantovani F., Capideville C.S., Preziosa A., Morganti F., Villani D., Gaggioli A., Botella C., Alcañiz M. (2007) Affective interactions using virtual reality: The link between presence and emotions. CyberPsychology & Behavior 10(1):45-56. DOI: 10.1089/cpb.2006.9993

Sedlmeier, A., & Feld, S. (2018). Learning indoor space perception. Journal of Location Based Services, 12(3-4), 179-214. https://doi.org/10.1080/17489725.2018.1539255