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Virtual Reality (VR) and Electroencephalography (EEG) in Architectural Design: a systematic review of empirical studies

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Abstract

Integrating human needs and desires into the design process has long been a crucial aim of design research. Despite advancements, architectural design still often overlooks the diverse dimensions of human experiences. In this context, the recent development of affordable and mobile brain-imaging devices using electroencephalography (EEG) presents an opportunity for a new approach to human-centered architectural design, especially in combination with virtual reality (VR). Despite existing EEG/VR studies in architecture, a comprehensive review of the methods used to translate EEG data into architectural design is lacking. To address this gap, this article presents a systematic review of empirical studies that use EEG in VR and investigate the impact of designed environments on users. Searches in the databases of Scopus, Web of Science and Science Direct resulted in nineteen articles utilizing both EEG and VR and focusing on an architectural perspective. The data analysis was performed qualitatively and is presented in summary-of-findings tables. The results indicate that in all reviewed studies, the framing environments affect specific brain regions and support different physiological, psychological, and cognitive functions. However, reliable conclusions about the impact spectrum of specific environmental features and associated event-related dynamics require further studies. Several gaps and challenges were identified. These include the need to develop comprehensive strategies for synthesizing data from a variety of sources, considering the distinct effects of familiar and new environments, and addressing limitations posed by sample sizes and demographic diversity. Additionally, long-term studies and investigations of the environmental impact on groups remain areas for future research.

Keywords

Neuroarchitecture, Architectural design, Brain imaging, Electroencephalography (EEG), Virtual Reality (VR), Machine Learning (ML)

Article type

Systematic review

1. Introduction

The human nervous system is highly specialized and organized to facilitate interaction with the environment, enabling us to process and respond to sensory information in a coordinated and adaptive manner [1,2]. Recent studies in cognitive neuroscience have revealed that the environment and its characteristics undeniably can impact human beings. While the brain governs our actions, and genes determine the architecture and organization of the brain, the environment can impact gene function, thereby influencing the structure of our brain [3,4]. According to Fred H. Gage [5,6] and John P. Eberhard [3], modifications in the environment might reshape the brain and consequently affect our behavior. This insight into the interdependence between behavior and the environment introduces significant new responsibilities for architectural designers.

What is more, the discovery of the *mirror mechanism* in the 1990s showed that the human brain represents “the body and its interactions with the world” [7] (pp. 72-75). For instance, whether we lift a cup or observe someone else lifting a cup, the same neurons in our brains are activated, simulating the corresponding actions in the relevant muscles. The *mirror mechanism* implies that the actions of other individuals or objects are mapped onto our own body representations through mirroring activity, often occurring unconsciously [8]. Consequently, humans are capable of sensing implicit and subtle impressions of their surroundings through their bodies, akin to perceiving the sculptor's fingerprints on a statue [9,10] through embodied simulation [11]. It is through this simulation process that the environment ultimately exerts its influence on human experience and well-being.

Furthermore, research has shown that people in the US, Canada and Europe spend around 90% of their daily lives within built environments [12-14]. The statistics underscore the crucial role of design in shaping the everyday experiences in technologically developed civilizations. Good design could greatly contribute to enhancing the *quality of life* for both individuals and communities. The concept of *quality of life* pertains to the extent to which human needs are met and the level of satisfaction or dissatisfaction individuals or groups perceive across various aspects of life [15,16]. Human needs and desires encompass a broad range of aspects, from survival and safety to self-esteem and personal fulfilment [17], all of which can be directly influenced by the environment's ability to provide or limit access to essential resources and stimuli, both on physical and emotional levels. Consequently, comprehending the intricate interplay between human needs, desires, and the environment underscores the significance of conducting experimental studies on the built environment and achieving greater mastery over architectural design.

Altogether, gaining insight into the long-term influence of the environment on human genes, as well as the processes of embodied simulation, could further elucidate the mechanisms by which the environment shapes human experiences. In addition, by analyzing individual responses and reactions to the environment, we can comprehend the extent to which the environment fulfils or constrains human needs and desires. Armed with these insights, we can strive to create supportive and inclusive environments that foster human *quality of life* (Figure1). It is worth noting that, in reality, there is no distinct boundary between long-term and temporary effects of the environment on humans. However, to enhance the understanding of the mechanism, they have been separated in figure 1.

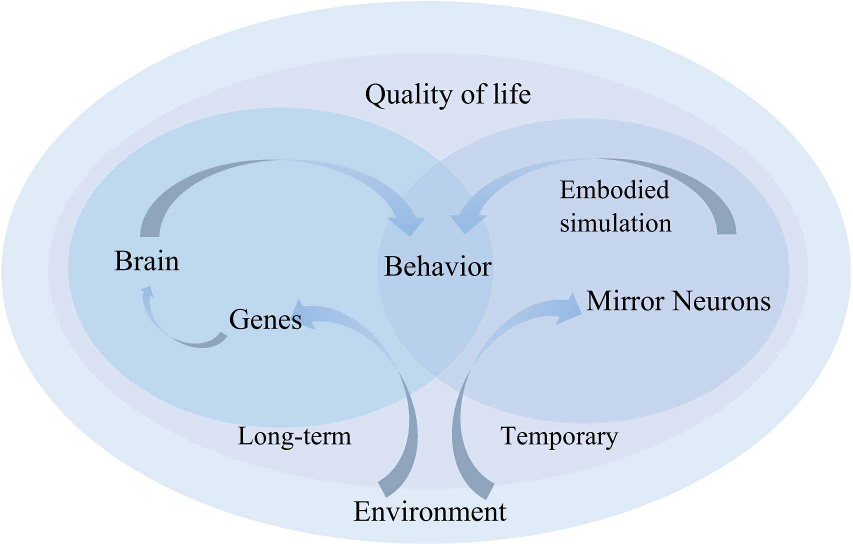

Figure 1 The schematic view illustrating the long-term and momentary impact of the environment on humans (Source: Author).

Studies investigating the influence of environmental characteristics on humans have primarily employed quantitative or qualitative questionnaires, interviews, observations, and descriptive methods, such as behavior mapping [18]. These methods have allowed researchers to analyze individuals' self-reported responses regarding environmental quality, satisfaction with meeting expectations, cognitive and emotional perception of the environment, as well as monitor the individuals' behavior within that context. However, these data were often non-immediate and subject to manipulation [19]. The advancement of cognitive neuroscience technology and brain imaging methods has opened up new opportunities to gather immediate data on how environments impact human experiences and well-being [20]. The recognition of the importance of these emerging opportunities let to the establishment of *The Academy of Neuroscience for Architecture (ANFA)* in 2002, and since its first biennial conference in 2012 [21], the collaboration between neuroscience and architecture has strengthened [3,22,23]. Following years of dedicated study within this collaboration, the term *neuroarchitecture* was coined to denote research at the intersection of neuroscience and architecture. In *neuroarchitecture*, brain imaging technology has assisted researchers in obtaining detailed quantitative data on individuals' physiological, psychological, and cognitive states in response to designed environments by monitoring their brain waves.

Neuroimaging methods were developed during the 20th century [24] and encompass a wide range of tools and processes, including positron emission tomography (PET), near-infrared spectroscopy (NIRS), magnetoencephalogram (MEG), functional magnetic resonance imaging (fMRI), and electroencephalography (EEG) [25-27]. Among these methods, EEG, a method dating back to 1924 [24], stands out as a valuable tool for architectural studies. Its mobility, capability to capture context-related signals, immediate reflection of postsynaptic changes, and millisecond-level temporal resolution distinguish it and make it suitable for tracking real-time changes in brain functioning [28,29]. With its feasibility and cost-effectiveness, recent portable EEG devices present a compelling prospect for integration into everyday design practice.

In this context, several studies have highlighted the suitability of virtual reality (VR) as a platform for facilitating the testing of immersive and embodied experience using brain imaging tools, such as EEG [30-33]. Combining VR technology and brain imaging tools will potentially allow architectural researchers to investigate the correlation between the effects of the architectural environments that they are in the process of designing on human experience, looping the gained insights back into the design process, which develops by being informed by user experience. While the use of neuroscience methods in architectural studies is still in its infancy, these technologies hold the potential to enhance people's well-being and reduce costs by enabling designers to evaluate the quality of designed spaces and their impact on users before construction, thus minimizing the need for subsequent modifications, which are generally only possible to a very limited extent.

This review aims to examine the application of EEG/VR in architectural research by reviewing relevant studies, with the following objectives:

- to systematically review and synthesize existing literature on the impact of the environment on various aspects of individual experience through VR experiments employing EEG.
- to review the methods utilized in the analysis of EEG data and its translation for architectural design.
- to categorize research methods, survey tools, analysis techniques, and measurement indicators.
- to discuss gaps in the current literature, providing insights that establish a basis for potential future studies.

While the detailed analysis of EEG data requires the expertise of a neuroscientist, architectural researchers utilizing EEG in their studies require a basic understanding of EEG data interpretation and its potential usefulness in the design process. This article initially aimed to include studies that compare the usage of EEG in both VR and physical environments. However, due to the limited number of such studies, the decision was made also to include articles that use VR but no physical environment for comparison in their research. This review highlights the methods, challenges, gaps and limitations associated with employing EEG in architectural research while also proposing potential areas for future investigation. Table 1 displays the primary methods for the analysis of EEG data utilized in the research studies that are analyzed in the main sections of this systematic review.

Table 1 Primary methods used for the analysis of EEG data

Methods	
Independent Component Analysis (ICA)	ICA is a computational method for extracting additive subcomponents from a multivariate signal recorded by the EEG [34].
Fast Fourier transform (FFT)	A mathematical tool for meaningfully analyzing signals by calculating the average frequencies in each time period [35].
Event-related spectral perturbation (ERSP)	This quantifies the average duration of shifts in the inherent EEG amplitude range caused by a series of comparable experimental occurrences [36,37].
Event-related potentials (ERPs)	This measures amplitude variations in the brain structures that are synchronized with a particular event, like cognitive activity [38].

Principal Component Analysis (PCA)	A multivariate statistics method that transforms a dataset with multiple variables into a reduced-dimensional space [39].
Long short-term memory networks (LSTMs)	A specific design of neural network architecture created to capture extended relationships within sequential data [40].
Network-Based Statistic (NBS)	A statistical approach that identifies connections within a brain network associated with diagnostic status, changing psychological contexts, or correlations with cognitive and behavioral measures [41].

1.1. Environmental effect on users

The studies selected for review investigate the influence of the environment on users with a variety of methods and techniques. In all nineteen studies explored further below, researchers examined the impact of the environment on physiological, psychological (behavioral-emotional), or cognitive aspects of human experiences (as presented in Table 4). In these experiments, researchers typically employed EEG in conjunction with a standardized test or related task. In several research projects, alongside EEG, researchers utilized additional small physiological monitoring tools, including electrocardiogram (ECG), heart rate variability (HRV), eye tracking (ET), galvanic skin response (GSR), and video cameras, ranging from larger scale setups to body-worn cameras. Participants were asked to engage in either a physical space or a pre-prepared VR environment and perform a previously designed test. The researchers then analyzed the results obtained from the test and the dataset collected by the monitoring tools. Since the volume of data obtained in such experiments is often large and comes from various sources, a coherent method for their analysis and subsequent integration into design processes is of great importance.

Recently, open-source platforms, such as *OpenSync* [42] and *Octopus Sensing* [43], have been introduced with the aim of automatically synthesizing multiple behavioral and physiological datasets in neuroscience-related experiments. However, the reviewed articles indicate that despite the introduction of these platforms, they have not yet been fully implemented, and most research teams analyze data according to their specific tests and experimental situations. Given the substantial potential of Deep Learning (DL) and Machine Learning (ML) classifiers and algorithms in data analysis [44-46], it is foreseeable that an increasing number of such platforms will be introduced and utilized in research in the near future.

1.2. How EEG assists in measuring the impact of environments on humans

EEG is a non-invasive measurement technique employed to map the electrical signals generated by active neurons in the brain, which are closely associated with the functioning of the nervous system [47]. The nervous system is a sophisticated network comprising the spinal cord, brain, and an intricate web of nerves extending throughout the entire body [48]. The human nervous system consists of two primary components, namely the Central Nervous System and the Peripheral Nervous System [49]. The peripheral part of the nervous system is further divided into a subset known as the Autonomic Nervous System (ANS) [50]. The ANS, comprising the sympathetic and the parasympathetic systems, regulates automatic physical functions such as respiration, heart rate, digestion, and the hormonal system [51]. The sympathetic and parasympathetic system produce stress and relaxation responses, respectively, to ensure the proper functioning of the nervous system [52,53].

By measuring the brain's electrical signals, EEG offers valuable insights into the operation of the nervous system. EEG works by placing electrodes from the front to the back of the skull [47], following the international 10-10 or 10-20 system, which provides optimal coverage of the entire skull [54] (Figure 2). These electrodes capture the brain's electrical activity in proximity to them beneath the skull, and the recorded activity is represented as waves in associated software [55]. The number and accuracy of the received electrical signals increase with a higher number of electrodes [56]. EEG signals are conveyed through various frequency bands, including “Delta (δ) (1-4 Hz), Theta (θ) (4-8 Hz), Alpha (α) (8-13 Hz), Beta (β) (13-30 Hz), and Gamma (γ) (30-40 Hz and above)”, offering insights into brain activation and providing valuable information about brain function [54].

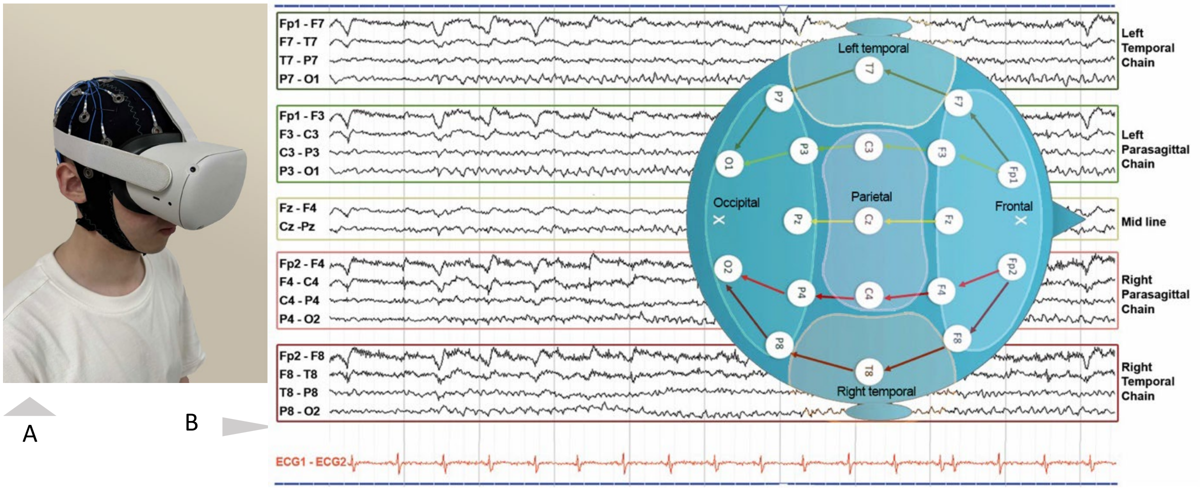

Figure 2 A) Participant wearing an EEG cap and VR headset (Photograph by XY, permission to reprint granted). B) Placement of electrodes on the skull and visualization of the resulting brain waves in the software. The number of electrodes used can vary. This image shows a basic sample of electrode placement (Source: Author).

In healthy individuals, there is a balance between the sympathetic and parasympathetic ANS systems under normal circumstances [50,57]. However, when influenced by external factors or changes in organ or hormone activity, the sympathetic and parasympathetic systems respond, and the difference in their actions can be monitored as a response of the ANS and brain dynamics using techniques such as EEG [50]. EEG has the potential to track real-time changes in brain functioning and the cognitive and emotional processes underlying behavior [28]. The information obtained from EEG provides insights into the impact of “emotional stimuli on brain and ANS activities and reveal the time-dependent interactions between these structures” [58]. Therefore, by employing EEG, researchers can gain insights into the influence of the environment on human cognition, emotion, and behavior. However, it should be noted that human states are multifaceted and influenced by cultural, educational and environmental contexts [59]. Table 2 presents a summary of the various types of brain waves associated with different human states, as documented in the studies conducted thus far.

Table 2 Characteristics of various brain waves associated with different human states.

Wave (Hz)	**Human state indication**
Alpha (α)	*Lower Range:*
Low 8-9	Recognizing objects through a navigation task; calmness, relaxed; disengagement *[60-62]*
High 10-12	calm, happy, sad and scared states *[63]*
	Upper range:
	The best state of learning and thinking *[59]*

	neutral emotions *[63]*
Beta (β) *Low 13-17* *High 18-30*	Engagement; focused; computing *[64]* decision making, direction-finding *[65]* attention and concentration *[59,66]* Task accomplishment causes sudden increase in the Fz, F3 and F4 Beta band *[61]* *Overdeveloped Beta waves:* Stress, anxiety, tension, aggression, causing incorrect decisions, interruption in the perception of the space *[67-69]*
Theta (θ) *4-8*	*Lower Range:* Unconscious, creative inspiration; deep meditation; shallow sleep state; spatial navigation *[70-72]* memory, perceptual, and emotion-related behaviors *[61,73]* *Upper range:* Frustration, dissatisfaction, high levels of Theta band activity in the frontal lobe (Fp1 and Fp2) indicates anxiety and fear, high demand and task difficulty *[62,74]* creative thinking *[75]*
Gamma (γ) *Low 30-40* *High 41-50*	Attention, cognition, perception, *[59]* happiness, stress relief; complex cognitive activity *[76,77]*
Delta (δ) *1-4*	Adult: deep sleeping, unconscious *[59]* Infants brain wave, empathy, intuition *[78]*

2. Methodology

Although some reviews of empirical studies investigating the impact of the environment on humans have been conducted, a comprehensive review of methodological approaches to translating EEG data into architectural design is lacking. To conduct such a review, studies were identified through the Scopus, Web of Science and Science Direct databases, with a complementary search in Google Scholar, to locate articles conducted in the VR environment using EEG to measure the influence of the environment on various aspects of human experience. While the use of neuroscience tools in architectural studies dates back to the early 2000s [79], it has gained increased attention and interest in recent years due to the availability of advanced, portable and affordable brain imaging technology that supports the development of the field of neuroarchitecture. Therefore, this review primarily focuses on empirical studies conducted in the past decade up until 2022. The following terms and keywords were utilized in the database search:

EEG and VR in architecture/ EEG and VR in architectural design research / brain imaging and VR in built environment/ VR and neuroscience for architecture / environmental effect on space user with EEG and VR/ neuroarchitecture and VR/ neuroimaging and VR in architecture.

Based on these search terms, a total of 1,973 articles were initially obtained (Science Direct: 1,808, Scopus: 35, Web of Science: 91, complementary search in Google Scholar: 39). After a screening process, 19 articles were selected for a detailed review based on the following inclusion criteria:

- The focus is primarily on articles that employed EEG to collect brain data. This choice was made because other tools, such as fMRI, PET, and MEG, are not suitable for inclusion in a mobile task or require an advanced operator to interpret the data obtained from these devices.
- Studies that conducted experiments in both VR and physical environments were prioritized, as the comparison between these two settings is important for analyzing human responses in different contexts. However, due to the limited number of studies conducted in both environments, research conducted solely in the VR environment was also included in this review.
- Since perception is action-oriented [80,81], the articles included in this review involved some form of action during the experiment, ranging from physical movements like walking and observing to performing cognitive actions.
- Studies that examined the impact of the environment or environmental features on human experience were included.
- The focus was on studies conducted from an architectural point of view rather than a mere psychological or neuroscientific one.
- Only articles published in English were included in this research.

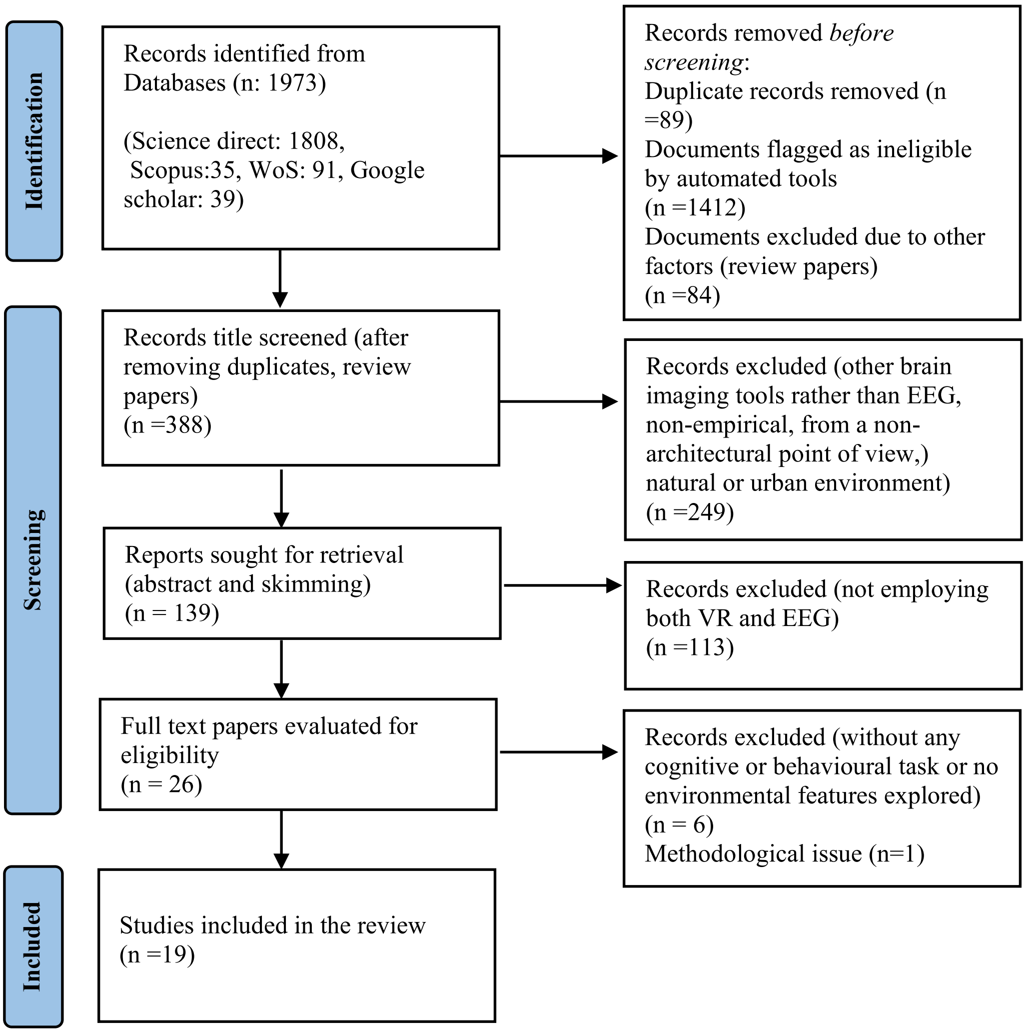

Figure 3 Study selection based on PRISMA 2020 flow diagram for new systematic reviews.

In the first phase, duplicate records and articles published before the last decade were excluded. Review articles were only inspected to identify additional research sources but were excluded from the main review round. The screening process also excluded studies that had no focus on architectural or built environment contexts and those that utilized brain imaging tools other than EEG. In addition, articles that did not incorporate both VR and EEG in their experiments, as well as those focused on natural and urban environments instead of the built environment, were excluded. The subsequent step involved removing articles that did not include behavioral or cognitive tests or those that did not examine the impact of an architectural element on human experience (Figure 3).

Based on a review of the abstracts, 19 journal articles met the inclusion criteria. After closer examination, Ji et al. [68] was excluded due to insufficient participant data and explanatory gaps. The study was conducted with only a single participant. No information was given about the participant's prior knowledge about the studied building that could have influenced the results, and no explanation was provided regarding how the researchers were able to link stress level changes to ceiling height changes when using a VR model that represented many other architectural features that could have influenced the stress level.

Data analysis was performed qualitatively (descriptively) by presenting SoF tables and summarizing the methods, tools, analysis, and findings to address the following research questions:

RQ1. Can the impact of the built environment on human individuals be measured through the use of EEG?
RQ2. What information can be derived from brain imaging (EEG) data, and how can architects and designers incorporate this data into the design process? Can EEG/VR data serve as a suitable alternative to time-consuming and costly post-occupancy studies in design research?
RQ3. What specific human attributes and capabilities are investigated in brain imaging studies conducted within VR environments, and what methodologies are used in these studies?

3. Review of published studies: Translating EEG data into architectural design

Following the identification of appropriate studies based on the listed criteria and their initial qualitative analysis, grouped by topic, this section presents a systematic review of the studies that utilized EEG/VR technology. The focus of this review is on insights that can assist with the development of methodology for translating findings from neuroarchitecture research into architectural design, and where applicable, key outcomes are discussed. Tables 3, 4, and 5 provide a summary of the research's focus on specific brain waves or regions, the method of data collection, data analysis, the impact of architectural features on the user, and the finding's implication for the integration of EEG data into an architectural design process.

3.1. Studying the effect of environmental form, geometry and height on users using EEG in VR

Investigating the impact of environmental geometry on individuals' emotions, Shemesh et al. [82] designed an experimental setting to measure and quantify participants' emotional reactions. Participants were equipped with EEG, GSR, and ET devices while observing 27 scenes with different features of proportion, scale, curvature, and protrusion, and were asked to answer two subsequent questions. The study discovered a strong correlation between changes in spatial geometrical features and human emotional states. The researchers acknowledged the complexity of measuring emotions and highlighted EEG as the most commonly employed method for evaluating emotional states, as indicated by their literature review.

During the analysis stage, they applied the Beta power ratio (computed as the sum of high Beta and low Beta divided by the sum of Theta and Alpha) to each recorded channel and searched for channels that showed a significant difference in average readings across the observed scenes. While they used the Beta power ratio extensively in their analysis, they did not provide information on why they chose this ratio as a significant measurement method or what specific characteristics of human experience or states can be inferred from it. Consistent with the findings of Banaei et al. [73], this study found a positive impact of large-sized curvature spaces on human emotional states.

Banaei et al. [73] produced different living rooms with various interior architectural styles in VR and discovered that curved shapes strongly affected the activity of a specific brain area called the Anterior cingulate cortex (ACC). By focusing on the ACC region, they identified a correlation between Theta activity and the specific features of the rooms, inducing pleasure and arousal. Importantly, they emphasized the critical contribution of the ACC to aesthetic experiences, which, however, requires further investigation in future studies. The results indicate that curved shapes have a strong positive effect on human emotional states and significantly impact perceptual aspects within a space. However, the effect was found to be short-lived, diminishing over time. This underscores the importance of conducting long-term studies to explore the influence of architectural features and environmental elements on individuals.

While most studies restrict participants' movement during EEG recording to minimize noise and artifacts, this study, which highlighted the importance of natural movement and environmental experience, discovered increased activity in the occipital region and posterior cingulate cortex during the exploration of the VR interiors [73]. Further research may shed light on the contribution of these regions to environmental perception.

Erkan [61] studied the impact of ceiling height on human cognition and emotion. The research utilized EEG-derived brain maps from all participants, generated a unified brain map, and calculated average frequencies in each period using FFT. The analysis of EEG data and video recordings of the experiment procedure revealed specific increases and decreases in waves at certain points along the test path. Erkan observed an increase in Beta waves at corners and decision points during forward movement, while Theta waves significantly increased during spatial navigation. Moreover, participants exhibited an upsurge in Theta-Alpha waves when observing objects within the pathway, indicating cognitive and memory activity. Task completion or reaching the end of the route resulted in a sudden increase in Beta waves at F3/F4 and Fz, leading to feelings of happiness or success. Individuals who successfully completed the route showed higher levels of brain activity in the frontal lobe (p. 419).

While Beta waves are typically correlated with attention, an excessive amount of these waves can induce anxiety, leading to agitation, irritability, and impaired decision-making abilities. An increase in Beta activity diminishes a person's ability to navigate correctly and recall objects in the environment, as seen when a subject cannot find the exit [61]. These findings, along with a comparison of task completion times, demonstrated that participants in the higher-ceiling space (3.5m) were quicker and found it easier to navigate the maze. They exhibited higher object mapping and recalling rates and experienced less anxiety compared to participants in lower-ceiling paths (2.5m and 3m).

3.2. Application of machine learning algorithms in EEG/VR research

In order to develop a comprehensive classification model that determines how motivating particular office designs are for individuals, Zou et al. [83] conducted a study focused on quantifying user experience within a VR office environment. Participants were instructed to perform various simple tasks while navigating through the environment, enabling the researchers to observe the influence of environmental factors on participants' brain waves. The study employed ML algorithms, including Support Vector Machine (SVM) and Artificial Neural Networks (ANN), for EEG data analysis and classification. The results showed that ANN achieved higher accuracy compared to SVM. However, the researchers emphasize the importance of conducting investigations involving a greater number of participants to establish more robust conclusions.

While the study made valuable contributions by proposing a learning model for design research, it lacked detailed explanations concerning the correlation between the introduced environmental factors (e.g., color, texture, sequence, layout) and a motivating office environment. Further research is needed to study these associations in more detail and gain a more comprehensive understanding of how specific design elements impact individuals' motivation in an office setting.

The research by Zou and Ergan [84] addressed the significant challenge of identifying suitable sensors and classifying individual experiences based on signal features in relation to architectural design research. The abundance of data involved in the research made it particularly challenging to identify relevant signal features. The authors argue that understanding biosensors and their corresponding signal features is crucial for detecting subtle variations in human physiology and assisting researchers in classifying human experiences in different environments.

To tackle this issue, the study developed a feature attribution model called SHAP (Shapley Additive exPlanations) using ML algorithms. This model facilitates the evaluation of the effectiveness of signal features in classifying the influence of different design alternatives on human experience. Through the application of SHAP, the authors found that EEG data captured human experiences better than other methods used in the experiment, such as GSR and photoplethysmogram (PPG). By identifying 25 signal features, the researchers assert that this represents a significant advancement towards automating the association of signal features with architectural design characteristics [84]. Furthermore, it establishes a foundation for a human-centered design platform that can be further developed through future studies.

The study specifically examined the effects of three bipolar design features - lighting, color, and layout - on human restorativeness, aesthetic pleasure, and anxiety, mapping signal features to design features. Despite developing a classification model, the study did not reach a definitive conclusion regarding the effect of these design features on human experiences. However, the experiment did reveal that the frontal lobe exhibited the highest activity in emotion-related responses, suggesting that measuring the frontal lobe activity could provide insights into emotion-related aspects of architectural environments.

Investigating the impact of the environment on human perception and work efficiency, Li et al. [72] examined three different spaces: a natural environment, a library, and an underground study room. They observed the greatest changes in the right temporal lobe before and after a scene transition. Statistical regression analysis revealed an inverse correlation between the duration of cognitive test completion and the energy ratio of the Beta rhythm. The Beta rhythm showed a positive correlation with human brain performance, indicating that greater Beta rhythm activity is advantageous for efficient task execution in the environment. Furthermore, participants in the natural environment showed the highest levels of Beta rhythm energy. The researchers argue that Beta rhythms are closely associated with the level of user satisfaction with decision-making and spatial perception. Conducting a statistical analysis by employing the SPSS software assisted the researchers in exploring the correlation between frequency band power and design features. While this project did not utilize ML, incorporating machine learning methods could enhance the ability to capture complex patterns, evaluate findings with greater accuracy, and assist researchers in constructing predictive models. Through the utilization of diverse datasets in specific ML models, researchers can assess the reliability of the model and develop a shared understanding over time.

Although Li et al. [72] made important contributions to exploring the impact of different environments on work efficiency and perception, the diversity of the test environments limited a deeper investigation into the effect of each individual environmental feature on humans. In a follow-up research project, Li et al. [85] focused on one of the spaces used in their earlier study Li et al. [72] –the underground office space – to gain insights into the environmental effect on human perception. Aiming for a better simulation of physical space, they improved the quality of the VR representation by utilizing laboratory environmental control (LEC) technology. This allowed them to control the influence of other variables such as sound, temperature, lighting, and air quality. Other studies have found that by increasing the quality of the representation in VR, the correlation between the EEG data recorded in the occipital brain region of participants in VR and real-world contexts also increases [86]. There is enormous potential, as the use of recent game engines like Unreal Engine 5 could further improve the quality of VR representation.

Narrowing down the scope of their experiment and using one kind of space only, the researchers investigated the effect of specific spatial design elements on human comfort and cognitive activity. The study included rooms with blue and red colors, a room with green plants on a wall, and a white room designated as the control space. It is noteworthy that they found a correlation between the average value of the high Beta-low Beta ratio and individuals' cognitive performances interpreting as environmental changes significantly affect cognitive function. Likewise, participants in the environment with the green wall exhibited the highest cognitive function and comfort. There is good potential for the incorporation of ML algorithms and platforms to develop a model for predicting the optimization potential of a space using the high Beta-Low Beta ratio and other aspects of human experience.

3.3. Research on well-being is an essential topic in EEG/VR studies

Stress relief is an essential indicator for assessing human well-being and a significant research topic for architectural researchers. For this systematic review, we studied three experiments [69,76,87] that focused on investigating the effect of the environment on participants' stress levels. Vaquero-Blasco et al. [76] proposed that VR can be a cost-effective substitute for expensive chromotherapy rooms for alleviating stress levels. To compare stress levels in physical and virtual chromotherapy environments, two groups of participants were exposed to a stressful situation and experienced different conditions in the experiment: a reference group in a real chromotherapy room and a test group in a virtual chromotherapy room. The researchers observed no significant difference in both groups' Relative Gamma (RG), i.e., the Gamma/Alpha and Theta ratio, which can be considered as an indicator of stress level.

The study by Yeom et al. [69], however, focused on Relative Alpha power as a measure of stress relief in their experiment. They examined the stress-relieving effects of a VR green wall by comparing human responses in settings without a green wall, and those with small and large green walls integrated into the interior design. Notably, this project utilized ML algorithms to eliminate EEG artifacts and analyze and synthesize physiological data such as EDA, HRV, and EEG. By employing Paired t-tests and Wilcoxon tests, the study explored the correlation between recorded brain waves and psychological and physiological measurements, highlighting significant stress relief in rooms with a small green wall. Surprisingly, the room with the large VR green wall exhibited an increase in stress levels. The results of this study are somewhat inconclusive in regard to their implications for architectural design, as it is unclear whether the experiment's VR green wall can be compared to a physical green wall. Like in research articles already discussed above, the researchers emphasize the importance of conducting further research with larger populations to achieve lower confidence intervals and a stronger correlation coefficient.

3.4. Comparing users' responses in VR and physical spaces

In response to the limited number of studies comparing VR and real-world settings, Kalantari et al. [88] collected human cognitive responses to both environments using EEG, ECG, EOG, and GSR. Since EEG data and cognitive test responses did not show a significant difference between the two conditions, this study reveals a consistency between human reaction to VR and real environments. Building upon this experiment, Cruz-Garza et al. [89] compared the cognitive responses of individual participants in virtual classrooms of different sizes and with and without windows. They discovered that Alpha power appeared to be greater in the left posterior temporoparietal cortex in the larger classroom compared to the control classroom with a smaller size. However, the cortical area shows no significant difference between the Alpha band between the class with one window and the class with two windows. The study further found distinct spectral and connectivity features in the frontal, central, and occipital lobes of the cortex in the two-window classroom. The symmetrical placement of windows throughout the visual field seemed to contribute to occipital bilaterality and parietal cross-hemispheric connectivity patterns. Using ML algorithms, specifically SVM, the researchers developed a predictive model to assess the differentiation of individuals' brain waves in the two different environments. While the study concluded that certain design features, such as room dimensions and window placement, can influence brain activity during cognitive tasks, the researchers remain cautious about drawing definitive conclusions regarding the effect of space on the human cognitive process. They emphasize the need for extensive testing and further research in order to make conclusive statements.

Marín-Morales et al. [90] utilized an SVM classifier to develop an "emotion recognition model" (p. 14) using EEG and ECG data. Their study compared the impact of two-dimensional, three-dimensional real, and virtual museum environments on participants' arousal and valence.

The EEG data collected underwent signal conditioning and artifact removal and were analyzed as frequency and functional connectivity datasets. The study revealed that self-evaluations of valence and arousal were slightly higher in virtual museums compared to real museums. However, the researchers acknowledged the need for further investigation, as they speculated that this result might be attributed to the novelty of VR and the participants' lack of experience with VR environments. The research findings indicate that brain synchronization[1], which refers to the coordination of brain regions, plays a crucial role in emotional experiences, whether in a real museum environment or a virtual one. One notable aspect of this study, in comparison to other studies exploring virtual and physical environments, is the focus on the quality of the VR scenes creating an exceptionally realistic world.

3.5. Utilizing EEG/VR research to inform the design of healthcare facilities

In an intriguing approach, Song et al. [92] conducted an experiment involving cancer patients to assess the impact of different environmental features, such as natural green and blue view and grey indoor space, on their restorativeness and health. Considering the existing evidence regarding the positive effects of natural spaces on mental restoration from their literature review, they investigated the impact on cancer patients, a particularly vulnerable target group. However, the study solely relied on Alpha brain waves as a measurement for evaluating participants' relaxation, and the EEG analysis was limited to the average Alpha wave values across different situations using ANOVA. The researchers did not report any artifact removal procedures or provide detailed analysis of the EEG channels. A significant aspect of this study is the duration of exposure to the environmental features, which ranged from three to five times a week. Other studies, in contrast, typically focused on shorter experiment periods, ranging from 30’ to a maximum of 150’ in one day. Additionally, the study evaluated the variation in participants' psychological responses from the first to the last test over a week-long period. Notably, the research findings suggest that as the duration of interventions increased, the capacity of diverse green spaces to alleviate mental stress (as measured through EEG) diminished. The researchers concluded that it may be most beneficial for cancer patients to experience exposure to nature up to a maximum of three times per week. However, an alternative conclusion could be that over time, with increased habituation, any environment loses its effectiveness. Therefore, experiments utilizing physiological measurements should be repeated over a longer period of time before drawing any definitive conclusions about the effects of environmental factors on humans.

Focusing on healthcare center design, Kim et al. [93] conducted a VR experiment with the aim of comparing the effects of different architectural features, specifically ceiling height, window ratio, and space ratio, on women in a postpartum care center. Their literature review highlighted that the Ratio of Alpha/Beta (RAB) could serve as a suitable indicator of emotional responses to stimuli. Consequently, they conducted statistical analysis on the collected data to examine the changes in RAB before and after stimulation, thereby determining the difference in RAB indicators. The findings of the study indicate notable variations in relaxation and arousal responses when individuals are exposed to different environmental elements. These differences were observed in specific EEG channels, namely F4 and P3, located in the left parietal lobe and right frontal lobe, respectively [93]. Like in other research articles, the researchers emphasized

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[1] For more detail about brain synchronization, see [91] Valencia, A.L. and Froese, T., What binds us? Inter-brain neural synchronization and its implications for theories of human consciousness. Neuroscience of Consciousness. 2020(1) (2020). https://doi.org/10.1093/nc/niaa010..

the need for further research with a larger number of participants to validate the potential of the RAB indicator in investigating emotional states induced by particular architectural features within the VR context.

To measure and compare different types of wayfinding in healthcare spaces, Kalantari et al. [87] conducted an experiment using EEG to examine participants' brain responses to different corridor designs in a VR environment. Employing one-way ANOVA and the *multcompare* function within MATLAB, they compared five EEG frequency bands across three different environments. The questionnaire and EEG data did not reveal considerable differences in levels of confusion, mental fatigue, and stress. However, the EEG data showed improvements in the choice of direction and orientation in environments with enhanced architectural features, graphics and color. The researchers interpreted the higher neural processing in the occipital cortex and increased cognitive engagement in the temporal region, observed when participants viewed signs and made decisions to continue their walk, as enhancements in orientation behaviors within an environment enriched with color, graphics, and architectural features. Nonetheless, the researchers cautioned against generalizing the findings to other settings without conducting further experiments. This study can serve as a valuable reference for empirical studies on EEG feature extraction related to wayfinding.

Building upon this experimental setup, the study by Zhu et al. [94] narrowed the focus and investigated "wayfinding uncertainty" in healthcare center environments. By employing an ML classifier, they developed a predictive model that highlighted EEG as a suitable method for identifying uncertainty in environmental navigation. They first interpreted the signal features of alpha, theta, and beta brain waves within specific time segments of navigation in the space, and then identified signal features correlated with wayfinding uncertainty using a Random Forest classifier. The experiment utilized Lab Streaming Layer (LSL) to record and synthesize EEG and VR data. The findings of the study demonstrated the potential of occipital alpha and frontal theta brain waves in revealing uncertainty in wayfinding. By developing a predictive model using SHAP, the researchers aimed to characterize the brain waves associated with wayfinding uncertainty within an environment. However, further investigation is necessary to fully characterize these brain waves.

3.6. Exploring the impact of colors on users through EEG and VR

Among the reviewed articles, the investigation of the effect of color on human experience has received significant attention, with nine studies exploring this architectural feature. Llinares et al. [95] conducted a study to examine the influence of cold and warm colors in VR classrooms on students' cognitive function, particularly attention and memory as well as arousal. Building on previous research, they identified higher Beta energy in the C3 and CZ bands as being associated with a high level of attention and cognitive function. Additionally, they considered the higher Beta energy in the F3 and FZ bands to be correlated with a higher level of working memory and attention. Consequently, the increase in Beta and high Beta band energy observed in students in the cold color classroom was interpreted as positively affecting attention, memory, and arousal.

However, the study by Liu et al. [66] led to contrasting results. They considered low and high Beta waves as manifestations of attention and found that warm color walls in classrooms had a positive impact on improving learning performance and attention compared to classrooms with cold and white walls. Additionally, participants reported higher levels of pleasure and relaxation in rooms with cold-colored walls. These findings were consistent across three measurements: subjective surveys, ECG, and EEG data. Investigating the effect of color on human cognitive performance involves considering numerous variables, including hue, saturation, and brightness, which can significantly vary [96]. In order to obtain accurate and reliable results, further research with consistent findings is necessary.

Bower et al. [97] investigated the impact of interior scale and color on functional brain connectivity using EEG in a Cave Automatic Virtual Environment (CAVE) environment. To establish a standardized condition, the researchers created what they considered to be a neutral room. Painted white, the room had only a chair and a closed door. The participants began in a resting state with their eyes open and were subsequently exposed to four different scenes where the sizes of the chair, door, and room were randomly manipulated. Finally, the participants were presented with a scene featuring a blue-colored room contrasting the achromatic (white) control room. The research revealed a correlation between Gamma and Theta waves and the perception of size and color in the environment, suggesting that design characteristics can impact cognitive functions and mental well-being. However, additional research is required to reproduce these findings and acquire a more comprehensive understanding of the neural mechanisms implicated. While the study focused on cognitive function, it did not report any specific cognitive tasks in its experiments and solely analyzed brainwave patterns to draw conclusions. Although the researchers' findings regarding the emission of Theta and Gamma waves are valuable, other studies have highlighted that the role of the Beta wave in cognitive actions is also crucial [61,66,85,95]. It will need to be further explored in future research.

Over time, researchers have become increasingly cautious in drawing definitive conclusions from their empirical experiments, often deferring to further research with a more diverse sample size. Nevertheless, the existing studies establish a foundation for a holistic approach to studying the impact of the environment on users by utilizing the latest neuroscience findings and VR technology. Tables 3 and 4 provide an overview of the reviewed research articles in terms of brain waves and brain regions studied, EEG data analysis methods, as well as the implications of the research findings for architectural design and the integration of EEG data into the design process. Figure 4 illustrates an overview of the EEG experiment analysis process, highlighting the integration of data obtained from various sources in EEG/VR studies.

Table 3 Summary of the brain waves, data analysis method, and the implications of the analyzed EEG data for architectural design research.

The numbers in the first column indicate the order of papers in the main body of the text.
*A * indicates studies implemented in both physical and virtual environments.*

No.	Brain waves/region	Analysis	Implications for architectural design and the integration of EEG data
2	Anterior cingulate cortex (ACC), Theta band activity 128 channels	Effect of various interior forms on emotional state activity, i.e., pleasure and arousal	The research concludes that curved interiors have a positive effect on the participants' emotional state. Yet, a strong initial impact of an environment on perceptual and emotional states was observed to quickly decline. Data from the ACC region of the brain, specifically synchronized theta activity, might provide insights into the aesthetic quality of designed environments. *2017 [73]*

3	Alpha, Beta, Delta, Theta Focus on F3/F4 and Fz	Exploring the effect of ceiling height, education, gender, and age on wayfinding and cognitive activities by providing a combined brain map as a power spectrum graphics	High ceilings (3.5 m) show higher efficiency in human cognitive processing, wayfinding, object mapping and recalling compared to spaces with ceiling heights of 3m and 2.5m. An increase in the amount of Beta waves correlated with a person's struggle to navigate a space and recall objects in the environment. As the study shows, such issues can be affected by architectural design features. *2018 [61]*
12 *	Alpha, Beta, Gamma, Theta 9 channels and 4 bands	Exploring the ability of VR to elicit comparable emotional responses to those experienced in real-life situations by examining valence and arousal	The study suggests that architectural environments can be effectively explored in VR, considering the high quality of their virtual representation. Data on brain synchronization offers insights into various emotional processes related to both VR and real environments. The research further shows that there is significant potential in the employment of machine learning for the analysis of data. For this study, the researchers developed a "emotion recognition model," using SVM. *2019 [90]*
4	14 channels of signals	Investigating the impact of motivational and non-motivational office spaces through changes in 4 design elements: color, texture, space layout, and sequence of spaces	The research concludes that further studies are required related to the impact of various design features of office spaces on motivation. The ANN model quantified individuals' experiences in a designed environment with an accuracy of 85%. To confirm these results more research is needed. *2019 [83]*
6	Energy of the Beta rhythm, right temporal lobe and 4 points (Ph1-4) F7, CP2, FC6, P3 32 channels	Influence of the environment on human mental perception and improved residents' satisfaction and work efficiency, the study compared a natural environment, a library and an underground study room	The research concludes that further studies about the effects of architectural design features on work efficiency and user satisfaction need to be done. A proportional relationship between work efficiency and the high Beta-low Beta ratio is observed. The natural environment showed the highest cognitive function and comfort. *2020 [72]*
8 *	8 electrodes at O1, O2, Fz, Cz, Fp1, Fp2, F7, F8 Gamma/Alpha and Theta	Investigating the effects of virtual Chromotherapy room with magenta, blue, and green lights in comparision to a real one, on stress reduction	The research concludes that VR simulations of Chromotherapy rooms can alleviate stress levels as much as physical Chromotherapy rooms The study confirms relative Gamma (RG), the ratio of Gamma power to Alpha and Theta, as a reliable indicator for analyzing stress-related studies. *2020 [76]*

10 *	Gamma, Alpha, Theta, Beta, Delta 57 channels	Exploring the comparability of virtual and real classroom in terms of individuals' cognitive activities	The study concludes that human cognitive reactions in VR and physical classrooms are comparable. The conclusion is based on a correlation between EEG frequency band power and ERP analysis. *2021 [88]*
14	RAB (Ratio Alpha/Beta), F4 and P3 channels 24 channels	The effects of varied architectural elements (Space ratio, Window ratio and ceiling height) on human brain response	The study concludes that when the window ratio exceeds 60%, both the space ratio and ceiling height significantly influence human arousal. Subtraction of RAB before and after stimulation and activation of certain lobes (the left parietal and the right frontal lobe) is associated with relaxation-arousal responses. *2021 [93]*
7	Alpha, Theta, low Beta and high Beta bands and EEG topographic map CP6, posterior and central areas 32 channels	Enhancing the quality of the underground office environment by examining individuals' comfort and feeling. Investigating higher activity in CP6, posterior and central region.	The study concludes that environmental changes generally affect human cognitive performance. A green wall was observed to lead to higher cognitive function. The correlation between a high Beta-low Beta ratio and cognitive function indicates that environmental changes affect participants' cognitive performance. *2021 [85]*
17	Beta in C3 and CZ High Beta in F3 and FZ 9 channels	Investigating the effect of the wall colors of the class (warm and cold) on the students' cognitive function of attention and memory	The study finds cold-hue-colored classrooms to positively affect arousal, memory and attention. Higher Beta activity in C3 and CZ, and High Beta in F3 and FZ are associated with higher arousal, memory and attention function. As this finding contrasts with the result of another reviewed study conducted by Liu et al. [66], further research is needed. *2021 [95]*
9	Relative Alpha power (RA) in occipital and parietal lobes Theta and Beta 14 channels	Exploring the impact of biophilic design (green wall) on stress relief, anxiety and mental fatigue via ML	The study finds that the integration of a small green wall in a VR interior provides stress relief, while a large green wall increases stress levels. A higher RA in the occipital and parietal lobes is seen to correlate with stress relief. Comparing virtual and physical green walls could potentially yield more conclusive results. *2021 [69]*

5	Frontal and occipital lobes 14 channels	Effect of 3 Bipolar design features (light, color, dark and layout) on human restorativeness, aesthetic pleasure and anxiety via EEGLAB. Developing ML feature attribution model (SHAP)	The study concludes that individual experiences in architectural spaces can be effectively measured with EEG devices and subsequently classified. Frontal lobe activity is seen to present a higher significance for classifying emotional responses of users to architectural contexts. *2021 [84]*
19	Almost all regions and waves Focus on Theta and Gamma in right frontal and temporoparietal lobes 64 channels	Exploring the influence of color and scale of interior environment on functional brain connectivity	The study concludes that changes in the size and color of interiors correlate with alterations in the Theta and Gamma waves. High-Gamma is observed in smaller rooms, and Theta is in blue rooms. As the researchers' literature review suggested a potential association of Theta with information processing and high Gamma with complex cognitive activity, they emphasized the need for future research. *2022 [97]*
11	Alpha, Beta, Delta, Theta and connectivity features 57 channels	Effect of different window placement and classroom dimension in VR on the neural dynamics of users via ML	The study concludes that there are diverse effects of architectural features on human cognitive activity. Larger classrooms exhibited a higher level of Alpha activity compared to smaller rooms, while there was no significant difference in Alpha power between classes with one and two windows. The variation in Theta and Alpha power across the frontal, parietal, and occipital lobes, along with shifts in information transfer from mid-parietal to frontal regions, is found to relate to variations in human cognitive activity. The researchers developed a predictive model using SVM to assess the differentiation of individuals' brain waves under different conditions. *2022 [89]*
15	Gamma, Alpha, Theta, Beta, Delta The temporal and occipital regions 128 channels	Investigating the effect of 3 different feature of healthcare space (enhanced architectural features, signs, and colors) on wayfinding behavior of users	The study concludes that enhanced architectural features lead to an increase in cognitive engagement and stronger orientation behaviors. Higher neural processing in the occipital region and significant desynchronization in the temporal region are associated with higher levels of cognitive engagement and stronger orientation behaviors. For a robust conclusion, further research in different settings is required. *2022 [87]*

18	Low and high Beta FP2 in frontal lobe 32 channels	The effect of different color walls on learning performance, attention and pleasure via finding relation between low /high Beta and cognitive tasks	The study concludes that warm-colored-spaces (red and yellow) increase learning performance and attention while cold-colored- spaces (green and blue) increase pleasure and relaxation. Increased learning performance and attention are associated with higher Beta power, and increased pleasure and relaxation are linked to lower Beta power. As this finding contrasts with the result of another reviewed study conducted by Llinares et al. [95], further research is needed. *2022 [66]*
1	Beta power ratio, 5 channels (Pz, T7, T8, AF3, AF4)	The influence of geometry of designed spaces on human emotion and viusal perception via diffusion map algorithms	The study concludes that the proportion, scale, curvature and protrusion of designed environments influence human emotion. It reports a strong correlation between changes in spatial geometrical features and human emotional states. The study focuses on Beta ratio, the sum of high Beta and low Beta divided by the sum of Theta and Alpha for the study of emotion. *2022 [82]*
13	Alpha band power	The impact of various environmental features, such as semi-open, open, and closed green spaces, as well as blue open space and grey indoor spaces, on restorativeness of cancer patients	The study concludes that exposure to natural environments can have a significant effect on a person's relaxation. Individuals exposed to natural environments three times per week showed the highest levels of relaxation. A further increase in exposure led to a decrease in the positive impact. High relaxation is found to correlate with high Alpha power. This study is unique in exposing participants to environmental features more than once a week, with exposure ranging from three to five times and highlights the importance of conducting long-term studies on the effect of environments on users. *2022 [92]*
16	Alpha, Theta, and Beta band power 128 channels	Navigation uncertainty in healthcare center environment using ML algorithm, Random Forest classifier	The study concludes that environments can be designed to support wayfinding and that EEG data provides relevant feedback about wayfinding in architectural contexts. Further research is needed to identify the design features that support wayfinding. Frontal Theta, as well as parietal and occipital Alpha and Theta are associated with wayfinding. Further research is needed to characterize the brain waves associated with uncertainty in wayfinding within an environment.

2022 [94]

Table 4 Methods used to analyze EEG data in empirical architectural research.

Analysis Method/Software	
Machine Learning algorithms (Artificial Neural Network (ANN), Support Vector Machine (SVM), Stochastic Gradient Descent (SGD), Multiple Artifact Rejection Algorithm (MARA), Leave-one-out-Diffusion map algorithms), Random forest algorithm	*[90] [83] [69] [89] [82] [94]*
MATLAB-based software, EEGLAB	*[73] [61] [69] [89] [76] [85] [95] [87] [97] [88] [66] [84] [94]*
Artifact removal (Bandpass filter to remove exogenous artifacts, Butterworth filter, depression filter, sag filter, ICs, PREP Pipeline) Independent component analyzes (ICA), SOUND algorithm)	*[73] [90] [83] [69] [89] [85] [87] [88] [76] [84] [94] [97]*
SPSS: ANOVA- Paired t-test- Pearson test- Spearman correlation coefficient- rank test-Kruskal Wallis test-Shapiro Wilk test and Wilcoxon signed Two-tailed t-test - Kolmogorov-Smirnov- Predictive Analytics SoftWare (PASW)- post hoc- Pearson's Chi-square-regression-	*[73] [61] [72] [76] [89] [93] [85] [95] [87] [69] [97] [88] [66] [82] [92] [94]*
Fast Fourier Transformation (FFT)	*[61] [83] [93] [69] [66] [84] [97]*
Event-related spectral perturbation (ERSP)	*[73] [87] [88]*
Event-related potentials (ERPs)	*[89] [85]*
Power spectrum diagrams via normalization, power spectral density (PSD)	*[84] [61] [90] [76] [88] [94]*
Visualization method (HiPlot, Tableau), topographic map, connectivity matrix, Network-Based Statistic (NBS)	*[85] [66] [97]*
EEG exclusive device software Emotive Insight system- Net Station 5 Geodesic EEG software- Mind Monitor application	*[82] [97]*
Principal Component Analysis (PCA)	*[73] [90]*
Time-series analysis program TeleScan	*[93]*

Table 5 presents a summary of the physiological, psychological, and cognitive experiences investigated in the reviewed articles and papers, as well as the measurements and tools employed to evaluate the impact of the environment on individual experience.

Table 5 A summary of the physiological, psychological, and cognitive aspects and the mean of measurement used in the reviewed articles and papers.

Biological tools and cognitive and behavioral measurements		
Physiological aspects		
Brain waves	EEG	*all reviewed studies*
Heart rate	HRV, ECG, PPG	*[88] [69] [84] [92] [90] [95]*
Eye movements	EOG, Eye tracker	*[88] [82]*
Skin responses	GSR	*[88] [84] [82]*
Comfort	Blood pressure (BP)	*[92]*
	Pulse oximeter	*[85]*
Restorativeness and health (relaxation)	Navigation task	*[84] [92]*
Psychological aspects		
Pleasure and arousal	Virtual SAM & Stroop test Interview, EEG	*[73]*

Emotional response (valence and arousal)	self-report survey, SAM, EEG, ECG Navigation, simple tasks, brain waves	*[82,90]*
Relaxation and arousal	Self-report survey, EEG	*[93]*
Motivation to work	Walking, EEG	*[83]*
Stress relief	state-trait anxiety Inventory (STAI), (EEG and HRV)	*[76]*
Stress relief, mental fatigue, anxiety	Subjective questionnaire	*[69]*
Satisfaction	Subjective questionnaire	*[72,85]*
Pleasure and relaxation	Bipolar questionnaire, PANAS	*[66]*
Aesthetic pleasure	Self-report survey, dwelling time, GSR, EEG	*[84]*
Mental health	EEG	*[97]*
Cognitive aspects		
Cognitive perception	Stroop test	*[72,85]*
Cognitive processes	EEG	*[97]*
Cognitive responses	Cognitive tests (a Visual Memory, the Benton, the Digit Span, Stroop, an Arithmetic Test)	*[88,89]*
Attention, learning and memory	Physiological test (EEG and ECG), tasks	*[66,95]*
Visual perception	Dwelling time, ET	*[82]*
Wayfinding	Questionnaire, navigation task, EEG	*[61,87,94]*
Work efficiency	Subjective questionnaire, EEG, cognitive task and test like Stroop, calculation	*[72]*

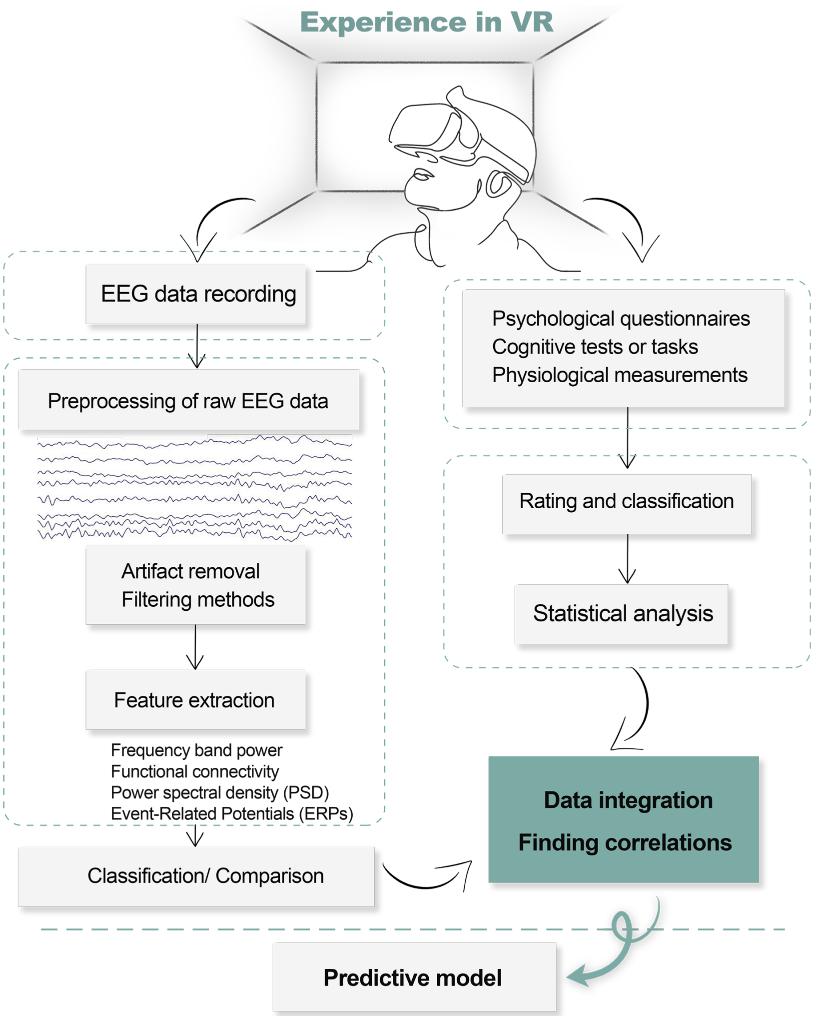

Figure 4 An overview of the EEG/VR experiment analysis process

4. Discussion

4.1. Avoiding bias in measuring the effects of designed environments on users

Professional designers have always been concerned with the effects that the environments or products they design may have on users. A common method to obtain information about these effects has been to utilize questionnaires to ask users about their feelings, emotions, and opinions. However, the impact of environments is often subtle and unconscious. Users might not consciously and immediately understand what the impact is [98,99], which means that it remains unreported in questionnaires. Additionally, consciously given questionnaire responses are often self-censored or manipulated, potentially contaminating the collected data [19]. In response to RQ1 (see Section 2), this systematic review of papers and journal articles published in the past decade affirms that brain imaging can provide immediate data and reveal the slightest variations in human brain activity [56], reflecting responses to different environments that can induce significant changes in human genes, brain, emotions, and behavior over time [3]. Although the field of neuroarchitecture is in its infancy, and researchers are cautious in making conclusive statements based on their empirical experiments, often stating that further research with larger and more diverse sample sizes is needed, there are first insights that are relevant to architectural designers. How the research findings relate to architectural design and what they imply in regard to the integration of EEG data in a design process are summarized in Table 3.

4.2. The combination of VR and EGG offers new opportunities for human-centered design

Furthermore, researchers have increasingly recognized the potential of VR as a platform that can facilitate the testing of immersive and embodied experiences. In response to RQ2, the studies that investigated the comparability of human responses in virtual and physical environments suggest that VR is an effective means to examine the effect of designed environments on users before construction, allowing for a trial-and-error process in the design processes. Testing designs in VR has become a viable and cost-effective alternative to building mock-ups. This review reveals a considerable increase in the number of publications employing the combined methodology of EEG/VR in architectural research within the past few years (Figure 5). Neuroarchitecture and its findings have the potential to contribute to the architectural design process in two ways:

- On one hand, the findings from numerous experiments that measure individuals' physiological signals and corresponding emotion questionnaires can be used to examine the influence of the environment and its features on humans. If these findings are consistently supported by empirical studies, robust models can be developed to integrate particular design features that are known to have desired effects into an architectural project.
- On the other hand, designers can assess their designed environments during the design process by employing VR and neuroscience tools, such as EEG, along with other behavioral and psychological assessments. The method can assist them in analyzing the impact of the designed environment and initiate changes if needed. They can determine the extent to which the project requirements are being fulfilled and identify areas for improvement. There is potential for a considerable reduction of the costs associated with the building of mock-ups or changes to an already built work, thereby significantly mitigating the risk of project failure.

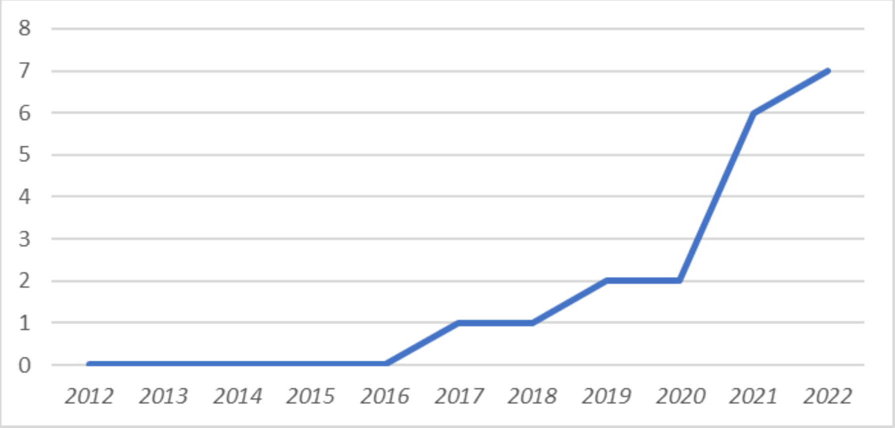

Figure 5 The number of publications using both EEG and VR in architectural research (Source: Author).

Both approaches have the potential to provide relevant information for designers and provide new opportunities for developing a user-centered design methodology. As research expands and data increases, this path will become increasingly evident, allowing for the identification of consistent answers while filtering out random data from the pool of results. Based on neuroarchitecture-related findings, a commonly accepted new user-centered design methodology can evolve, incorporating quantitative and qualitative methods, as well as the study of experiences in immersive VR environments.

In addition, the environmental features of buildings, whose spatial qualities are appreciated across cultures and over extended periods of time, are not yet fully understood. It remains a mystery which environmental features create specific emotional or perceptual reflections leading to a pleasant feeling or aesthetic experience within a space. However, neuroaesthetics, through the study of the nervous system in individuals exposed to the same environmental stimuli, can guide researchers in identifying a common pattern of responsive systems [100]. A recent neuroaesthetics study investigated the design features in hotel buildings that evoke a sense of hospitality in consumers, revealing the role of the sensory-motor system in evaluating intricacy, smoothness, and naturalistic characteristics of architectural spaces [101]. Integrating identified patterns with current neuroscience findings on the human emotional and cognitive system can assist in unveiling the secrets of the success or, in contrast, the failure of constructed spaces. Designers can acquire insights and subsequently translate these patterns into criteria for human-centered design, fostering the creation of new spaces that retain successful features while avoiding undesirable ones.

4.3. Further research required to develop better frameworks for measuring human responses to the built or designed environment

Regarding RQ3, the examination of physiological, psychological (emotional-behavioral), and cognitive aspects are among the key factors in studying the influence of the environment on different aspects of individual experiences (as illustrated in Table 5). However, it is evident that the standard tests commonly used in cognitive sciences and psychology for architectural experiments will require a critical review and constructive interactions among architects, psychologists, and cognitive science researchers. These tests can be adapted and modified to suit environment-based experiments, with careful consideration given to the environmental factors that might impact the results.

Additionally, this review highlights the growing interest in the usage of ML and DL algorithms for collecting and synthesizing large amounts of data from various sources that record physiological and psychological states. While the use of such methods is not yet prevalent, some studies have utilized *Lab Streaming Layer* (LSL) software [89,94] and ML classifiers [69] to collect and synthesize data from multiple resources. ML and DL have also been employed in six papers to analyze extensive data and develop predictive models [82-84,89,90,94] to accurately assess the effectiveness of specific environmental features. Considering the high potential of ML and DL in studies that employ mixed methods to evaluate the environmental influence on human experience, in the future, likely a greater collection of predictive models will be developed to assess the effects of different environmental features. The development of an overall blueprint for several models can contribute to the creation of flexible and comprehensive software and applications.

There are indications that the level of expertise plays a role in cognitive responses. For example, Kirk et al. [102] investigated the effect of expertise on individuals' perception of aesthetic value and discovered that experts tend to integrate new information into their existing knowledge framework, utilizing this knowledge to organize their aesthetic judgments. The research also demonstrated that expertise influences the activation of brain lobes correlated with both cognitive and aesthetic processing [102]. Similarly, Petukhov et al. [103] found that professional skiers do not exhibit a range of Gamma waves when skiing. This suggests that individuals may not need to exert significant intellectual effort to perform certain tasks or activities once they have reached a professional level [103]. Moreover, long-term exercise has been found to affect the neural correlations of work performance. As individuals specialize in a particular activity, the type of brain activity and wave production during training shifts from more "prefrontal cortex activity (central-executive) during early learning to more specialized parietal cortex activity" [104] (p. 520). Considering these insights, it is crucial to consider the levels of expertise of a study's participants as a variable when conducting cognitive tests and collecting data, especially if specific waves need to be observed in the experiment.

This review reveals the significant potential of neuroarchitecture in studying the relationship between humans and the environment. However, the use of brain imaging tools in architectural research necessitates trained researchers with multidisciplinary knowledge, in architecture and cognitive neuroscience, computer science, and environmental psychology, to effectively employ brain imaging tools and interpret their results. Neuroarchitecture researchers can play a pivotal role in bridging architectural paradigms and neuroscience findings, thereby enriching our understanding of the human-environment relationship. By investigating the characteristics of existing buildings, they can offer new perspectives on design criteria and environmental features. Furthermore, through the recruitment of neuroarchitecture researchers, architectural firms could study the effect of their designs on users before construction, in support of a human-centered approach to design, enhancing the potential of the designed spaces to respond to users' needs and desires in projects of various scales.

4.4. Gaps and limitations

EEG/VR research is in its early stages within the fields of architecture and the built environment, but it is experiencing rapid growth. Despite various empirical studies examining the impact of the environment on human experiences and attempts to collect quantitative and immediate data, there are still several areas that remain underexplored. The following paragraphs highlight some of the gaps and limitations in neuroarchitecture research:

- *Limited number of participants and lack of demographic diversity:* Participants in EEG/VR studies are often university students, which may not provide a comprehensive representation of the broader population, particularly in terms of age and cultural background. The extensive amount of EEG data collected in these studies often requires significant time for analysis, making it challenging to include more participants in the experiments. Table 6 demonstrates the distribution of sample sizes and test conditions in the reviewed articles and papers.

Table 6 Overview of the reviewed studies: number of test conditions and participants, and duration of the tests.

	Number of test conditions	***Number of participants***	***Experimental process duration***
[73]	5 (4 rooms (17 scenes for each) + 1 control room)	40 + 15 (2 phases)	
[61]	3 (Mazes with different ceiling height)	343 (340 finally)	
[90]	4 & 2 (in 2 phases)	60 (45 finally)	
[83]	4 (Color, texture, space layout and sequence in office)	34	40'

[72]	3 (Natural environment, library, and underground study room)	30	50’
[76]	4 (Chromotherapy rooms-ambient light colors: magenta, blue, and green)	20	1 hour (18’ main experiment)
[88]	2 (Virtual and real classroom)	25	
[93]	6 (Postpartum care center; ceiling height, window ratio, and ratio of space) (3*2)	33	+9’
[85]	4 (Typical underground office: red, blue, green wall included and conventional)	30	40’
[95]	2 (12 cold and 12 warm color scenes)	160	60’
[69]	3 (Small and large green walls included rooms+ 1 control room)	27	37’
[84]	6 (Natural light, artificial light- bright color, dark color-symmetrical, asymmetrical layout)	89 (in 3 groups)	40’
[97]	6 (Scale: 75%, 125%, 150%- color: white and blue + 1 control room)	66 + 18	
[89]	4 (3 different window placement and classroom dimension + 1 control room)	29 (23 finally)	
[87]	3 Healthcare center- enhanced color, graphics, and architectural features + 1 control space)	81 (63 finally)	90’-120’ (20’-30’ main experiment)
[66]	5 (Green, blue, white, yellow, red wall colors)	34	110’
[82]	4 (different proportion, scale, curvature and protrusion in 27 scenes)	112 (89 finally)	40’
[92]	5 (semi-open, open and closed green space- blue open space and grey indoor space)	70 (63 finally)	3-5 times in a week (35’)
[94]	10 corridors and navigational tasks in a healthcare center environment	34 (30 finally)	120’- 150’

- *Lack of longitudinal studies:* The reviewed studies have primarily focused on investigating the immediate influence of the environment on users' brain momentary activity and nervous systems. However, there is a notable absence of research investigating the long-term effects of the environment on individuals. Only one study, conducted by Song et al. (2022), involved participants being exposed to the designated environment 3 to 5 times a week. Human interaction with the environment is a continuous and long-term process, and it is important to understand how the effects of the environment may change or evolve over time. It is possible that the observed effects are transient and fade over time [73], or that prolonged exposure to certain environmental features attenuates their effects [92]. Therefore, conducting longitudinal research would provide valuable insights into the lasting influence of the environment on individuals, and it is a crucial area that requires further investigation.

- *Comparison of the effects of familiar and new environments on individuals:* The novelty of an experimental setup might influence the participants' emotional responses [90]. The impact of an environment to which we are accustomed and in which we have spent significant time might differ from that of a completely new environment. However, this specific aspect has not yet been thoroughly investigated.
- *Lack of a unified and commonly accepted strategy for integrating data obtained from various sources:* The research projects of the reviewed papers and journal articles operate with diverse data collected from different quantitative and qualitative sources, such as interviews, questionnaires, tests, tasks, brain imaging, eye trackers, GSR, and HRV which requires a robust strategy and inter-data analysis to synchronize data and identify any correlations between them. While 11 papers (55%) used EEGLAB to remove artefacts from EEG data, only 7 papers (35%) employed ML and DL to synthesize and analyze data or develop predictive models. Despite the potential of ML and DL, they are still not widely utilized, and most researchers follow a specific method that they consider compatible with the conditions of their research project. The differences between the individual methods limit the possibilities of comparing and validating different data sets and findings from various studies.
- *Involving participants in active roles during experiments:* While perception is considered an action-oriented process [80,81], researchers tend to minimize participant movement in EEG studies due to the artefacts it can introduce in the data. Consequently, in 13 studies (65%), participants were instructed to sit and, at most, use hand controllers to engage in movements within the VR space or perform tasks. Four experiments (20%) involved participants standing still and walking through teleportation. Only three studies (15%) allowed the participants to walk in the space freely. However, none of the studies involved participants engaging in tasks that required movement, such as drawing, solving puzzles, tackling obstacles, etc. Incorporating interactive environments and designing task-oriented activities could be explored as potential options for future research.
- *Exploring a wider range of cognitive activities:* Research on the environmental impact on humans has primarily focused on fundamental cognitive processes, such as memory and attention. However, a broader range of cognitive activities, including learning, writing, reading, problem-solving, speaking, programming and creativity-related activities, have not been adequately studied in this context. Future research should expand the scope of cognitive activities investigated to gain a better understanding of the influence of the environment on human cognition.
- *Lack of research on the impact of the environment on teamwork:* There is no study yet that employs EEG to investigate the effect of designed environments on group work and the interaction of multiple individuals.
- *The complexity of the real world and its experience compared to the laboratory environment:* Despite the advancements in research, laboratory and controlled environments are far from real-world scenarios, which have atmospheres that cannot be fully reproduced in virtual environments. To address the importance of controlling environmental variables, Vittori et al. [105] developed an experimental set-up, which they named the *NEXT.ROOM* and which enables precise control and monitoring of environmental comfort factors such as temperature, lighting, air quality, and sound. Additionally, two reviewed studies [72,85] utilized *Laboratory Environmental Control* (LEC) situations in their experiments to control environmental variables. Developments, such as *NEXT.ROOM* and LEC, can assist

researchers in exploring the effects of specific design features within a highly controlled and consistent environment.

- *Insufficient consideration of environmental features:* Environmental features such as form, color, height, light, sound, smell, temperature, humidity, movement, etc., play crucial roles in influencing human responses. However, due to the complexity of analyzing multiple variables simultaneously, experiments tend to focus on a limited set of variables, making it difficult to draw definitive conclusions about the impact of specific design elements and forms on human responses. The following figure illustrates the architectural features that have been investigated in terms of their effects on human experiences, along with the number of reviewed papers dedicated to each feature.

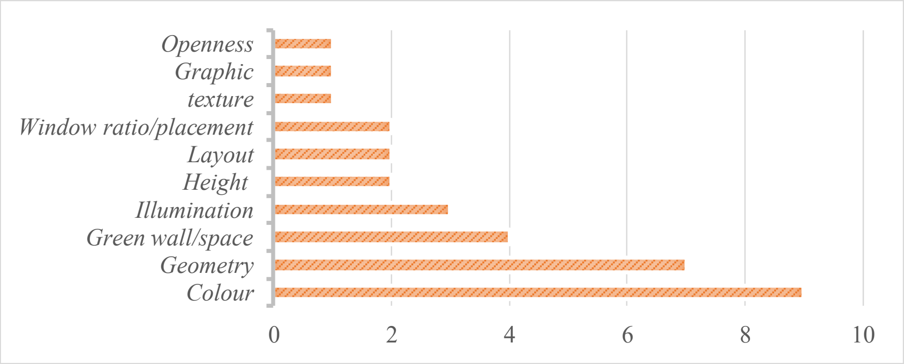

Figure 6 Architectural features and the number of papers exploring their effects (Note: Some features have been investigated together in one paper) (Source: Author).

- *Technical challenges:* Wearing a relatively heavy VR headset with an EEG cap and other gadgets, such as a body-worn camera, can disrupt the body's regular routines and put the mind on alert. This situation differs from normal living conditions, and additional research is needed to explore the influence of these technical prostheses on the results obtained from VR and EEG studies.
- *Technological constraints:* EEG devices are sensitive to movement and other extraneous activity, which can result in noisy data. While there are some methods to remove the artefacts, such as ICA and band-pass filters, researchers attempt to minimize participant movement and activity. However, these restrictions may potentially affect participants' behavioral and cognitive states, which should be further investigated.

The issues mentioned above provide potential areas for future research to improve our understanding of architecture and its impact on humans. Overall, despite the technological limitations and the large volume of data, there is a need for more experiments in various conditions and with more diverse participants before more concrete conclusions can be drawn about the effects of the built environment and its elements on physiological, psychological, or cognitive aspects.

5. Conclusion

This journal article conducts a systematic review of studies that integrate quantitative and experimental methods from neuroscience within an architectural research context to complement existing observational studies, offering a more comprehensive understanding of the complex interaction between individuals and the built/designed environment. The review focused on studies employing EEG in VR. This systematic review describes, for each of the reviewed papers and articles, the methodology, tools, and analysis techniques used to collect and analyze EEG/VR data and provides architects with a better understanding of how to interpret these data in design research. Interpreting EEG data typically requires the knowledge of a neuroscientist, and yet interdisciplinary research in the realm of neuroarchitecture is growing with increasing interest in conducting further experiments. While the use of the large variety of methods and specialized terms in the emerging field of neuroarchitecture can be overwhelming, this systematic review assists with basic understandings, providing descriptive summaries of the employed techniques to facilitate a better understanding for those outside of neuroscience.

The studies examined in this review demonstrated a broad spectrum of environmental effects on the human state. These effects included the positive impact of design that integrates plants in interiors on stress relief [69], relaxation [92], cognitive function [85], and work efficiency [72]. Investigations into the influence of color on users revealed some inconsistencies. One study showed that cold-hued spaces have a positive impact on memory and attention [95], while another found higher attention and learning performance in warm-colored environments [66]. Other studies explored the positive impact of enhanced and clear architectural features on wayfinding [87], the influence of proportion, scale, and curvature on human emotion such as pleasure, arousal and valence [73,82], as well as the effect of ceiling height on cognitive processing and wayfinding [61].

Notably, research affirmed that brain activity and cognitive performance were indeed influenced by environmental features such as color, form and scale [85,89]. Furthermore, there was a demonstrated consistency in human cognitive activity across virtual and physical environments [76,88]. However, the researchers highlight that there is still insufficient research to draw definitive conclusions about the impact of the environment or environmental features on human experience. The key problem is that it is not possible to assign a specific frequency band power to particular human psychological or physiological states. To achieve more concrete results, further research is necessary, including larger sample sizes and repeated studies under different conditions and in different environments. The utilization of advanced analysis methods such as ML and DL algorithms would further assist in the comparability of different research studies.

The influence of the environment on various aspects of human experience, including physiological, psychological, and cognitive aspects, can be investigated using a range of methods such as questionnaires, interviews, and standard cognitive, psychological, and physiological tests, along with the use of EEG devices. By integrating the findings obtained from the analogue methods and combining them with the analysis of the data derived from EEG using ML and DL, designers and researchers can gain valuable insights into the impact of the environment on specific aspects of human experience. These insights can subsequently be applied in the design process to assist with the integration of human factors. As neuroscience and VR technologies continue to advance, researchers will have more opportunities to study these tools, which over time, will create less disruption and increase accuracy. Considerations for future studies that could contribute to this research field include:

- Exploring the influence of designed environments on diverse cognitive aspects, such as creativity, critical thinking processes, planning, problem-solving, and decision-making.

- Conducting long-term investigations into the lasting effects of designed environments on human cognition, going beyond short-term and temporary studies.

- Ensuring participant diversity by including individuals from various cultures and representing a broader statistical population.

- Including participants in action in experiments rather than in passive roles.

- Enhancing creative tasks and tests to effectively measure the impact of designed environments on cognitive, emotional, and physiological dimensions.

- Developing strategies to seamlessly integrate data obtained from different sources into the architectural design process.

- Exploring the impact of designed environments on teamwork dynamics.

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